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A High Performance Fiber Optic Telemetry Link for Use in a Space Radiation Simulator

by James C. Blackburn
Jonathan Vanderwall
Raine M. Gilbert

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... DNA ... task X... XVE, work unit 00035,
... Optic Link Development ...

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and Development Command
Harry Diamond Laboratories
Adelphi, MD 20783

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10 to the 8th power

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The transmitting end of the fiber optic link is designed to operate in a nuclear and space radiation simulator. It will function without noise increase or other degradation at up to approximately 10^8 rads(Si)/s of 1-MeV gamma rays and at cryogenic temperatures. The response is linear analog, with a bandwidth of 12 kHz to 350 MHz. Signal inputs are balanced with millivolt sensitivity. All functions are remote controlled through an RS-232 computer interface so that unattended operation is possible. Complete circuit diagrams, a discussion of the design, and test results are given.

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1 SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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1. INTRODUCTION

This analog fiber optic system was designed to provide a dielectrically isolated, wideband means of conveying signals from electrical sensors mounted within or on a test object to remotely located digitizing oscilloscopes. Because the fiber optic transmitter is near the sensors, it shares the vacuum, temperature, electromagnetic pulse (EMP), and ionizing radiation experienced by the test object. Even in this hostile environment, the transmitter must transmit the analog data without even momentary upset. The receiver/controller is colocated with the recording oscilloscopes and therefore need not be designed to perform in such an extreme environment. The fiber optic link can be thought of as being a remotely programmable oscilloscope vertical plug-in, and clearly should have bandwidth and dynamic range commensurate with that of the recording apparatus.

The entire analog fiber optic link is shown in the photographs of figures 1 and 2 and in the much simplified block diagram of figure 3. The transmitter, which during use is located at the equipment being monitored, is complete as shown in figure 2. This single unit contains all the circuitry shown at the left of the block diagram of figure 3, including batteries. The receiver/controller is located near the data recording equipment, typically an oscilloscope. The circuitry in this unit is shown in the right-hand side of figure 3. These two units are interconnected by two single optical fibers which may be of almost hair-like diameters if required. Typically, the tiny fibers are within a protective covering of a few millimeters diameter in order to provide mechanical protection. Two separate fiber channels are used—one to carry the analog signals and the other, a digital link, to effect the required remote control of transmitter functions. Essentially, a selected input signal directly modulates the laser diode, the output of which is conveyed to the receiver via a graded-index fiber. The analog signal is recovered by a high-speed photodiode, amplified, and made available to the recording instrumentation. Special features of the system include laser bias stabilization by feedback, electronic means to suppress modal noise, an effective receiver automatic gain control (AGC), onboard remote calibration signal, exceptional transmitter standby time, and complete remote control of all transmitter functions, either by the

Figure 1. Controller/signal receiver for optical link. All functions of remote transmitter are controlled by optically transmitted commands from controller.

receiver/controller or by a superintending computer.

The remainder of this report describes the rationale of the circuits in considerable detail. Test data supporting the performance of the system are also presented briefly, with references. Lastly, some lessons learned in the use of the apparatus are outlined, along with suggestions for possible improvements.

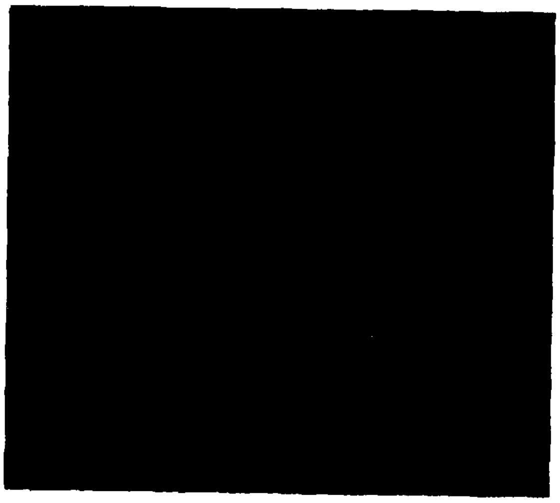

Figure 2. Exterior view of remote signal transmitter. Transmitter converts high frequency electrical inputs into optical signals which are coupled by fibers to receiver (fig. 1). Ruler is marked in centimeters.

2. FIBER OPTIC TRANSMITTER

Figure 4 details the transmitter subsections. It is convenient to begin by tracing the analog signal path.

2.1 *Baluns and Input Selector*

Four separate sets of differential inputs are provided, each set leading into a balun. The baluns exploit the isolating properties of ferrite cores and the hybrid properties of the Wheatstone bridge to provide good common-mode rejection up to 500 MHz. Because both inverting and non-inverting inputs are matched independently, either input of a pair may be driven single-ended without terminating its fellow. The four balun outputs are applied to a binary tree of three single-pole double throw (spdt) relays which select the desired channel. These relays are TO-5 size and can be embedded in 50-ohm microstrip without substantial reflection.

The principle underlying this balun is not new, having been well-known in 1920,[1] but its application to very wide baseband is uncommon. This type of balun has considerable advantage over the conventional type in that it does not eliminate the

[1] *G. A. Campbell and R. M. Foster, Maximum Output Networks for Telephone Substation and Repeater Circuits. AIEE Trans.* **39**, *Part 1 (January to June 1920), 231-280.*

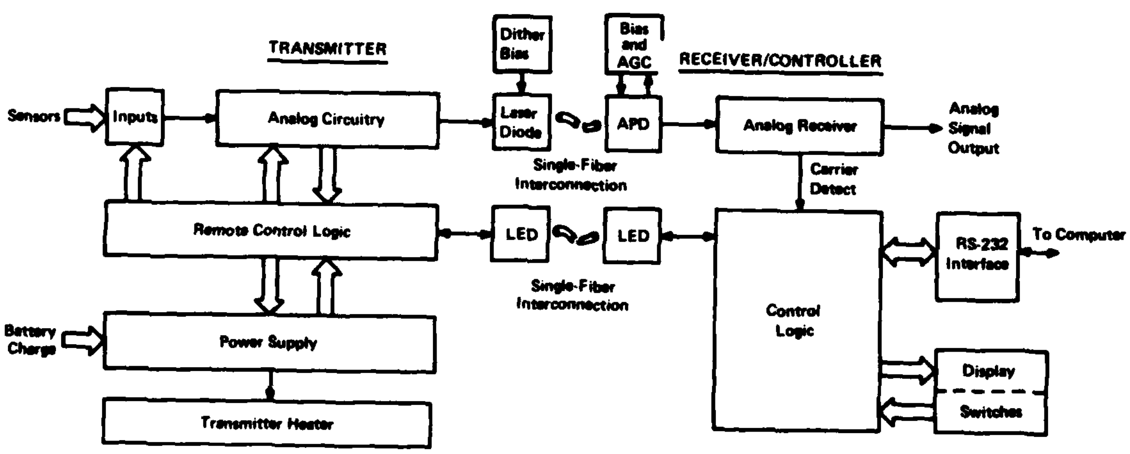

Figure 3. Block diagram of entire transmitter-receiver-controller system.

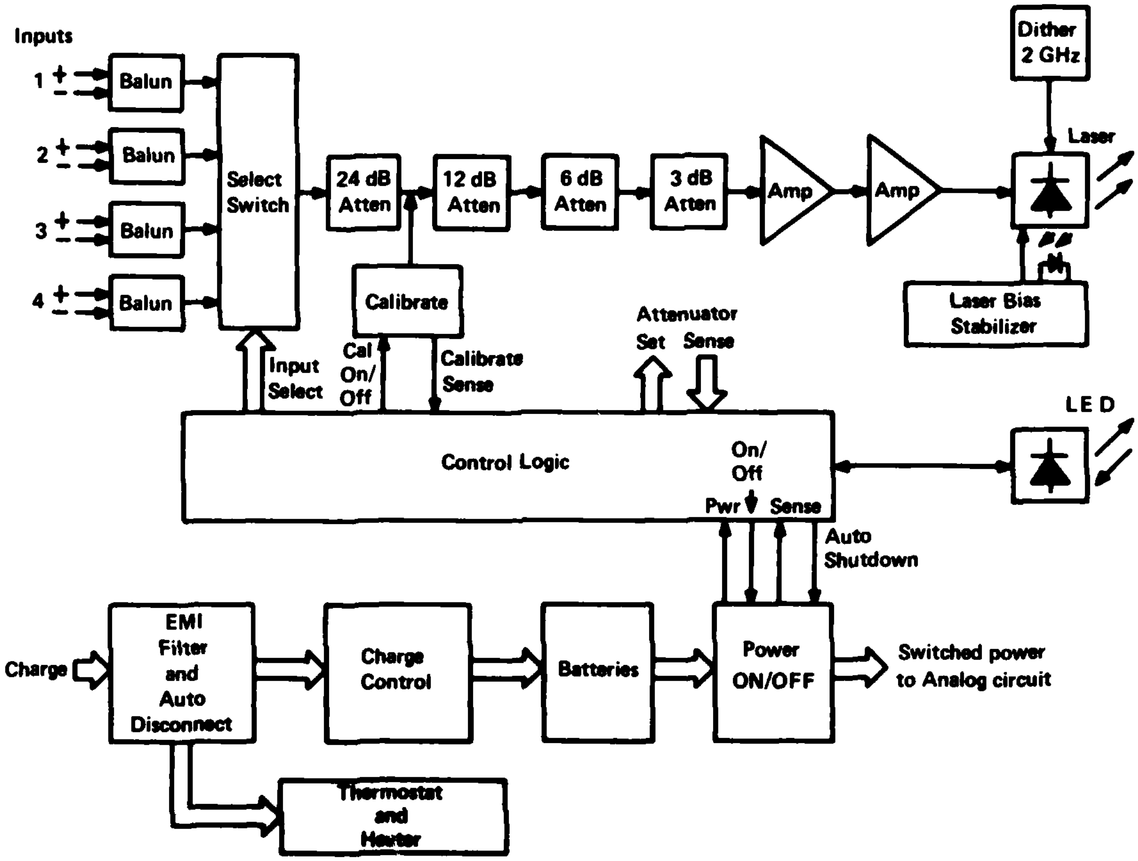

Figure 4. Block diagram of remote signal transmitter.

common mode by reflection. It also does not have preshoot and therefore is usable at very high frequencies.[2] Partly redrawn as figure 6, figure 5 is shown to be a Wheatstone bridge with all arms of equal resistance, namely $Z_0 = 50$ ohms. Note that in figure 5 there is a triangular block marked "FLOAT." This is achieved in the typical balun by winding a length of semiflexible coaxial cable on a toroidal ferrite core. In our balun, cores of high permeability (Indiana General AR-9708) are slipped over straight sections of semiflexible coaxial cable (coax) to achieve a similar result. This avoids the change in electrical length which occurs when coax is strongly bent, as in winding onto a core. Because the cores are electrically conductive, a 0.001-in. Mylar sheet is cemented around the semiflexible coax to insulate this unwanted resistance from the output. Normally, such a transformer is used for pulse inversion by grounding the center conductor at the output end and taking the output from the shield. However, there is no necessity to ground either side of the output. Therefore, in figures 5 and 6, the inverting input, having passed through such a transformer, can arbitrarily be connected across the bridge with

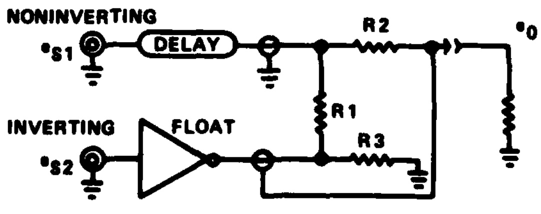

Figure 5. Block diagram of balun.

[2]*Jonathan Vanderwall, An Improved Balun for the SXTF Fiber Optics Link, Proceedings of the Fiber Optics in the Nuclear Environment Symposium, Harry Diamond Laboratories, March 1980, Vol II, Radiation Physics (DNA 5308P-2).*

neither terminal at ground. The noninverting input signals merely pass through a piece of cable equal in length to that in the inverting input before they are impressed across the opposite diagonal of the bridge.

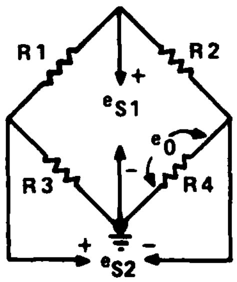

Figure 6. Schematic of balun. Signal line e_{S2} is floated by ferrite isolation.

The signal polarities drawn in figure 6 refer to common-mode signals. It is thus possible to see by inspection that common-mode signals cancel in R4, the load. (Obviously, cancellation occurs also across R1, but both sides of R1 are aboveground, which certainly limits the practicality of retrieving signal at this point.) Furthermore, the inputs are isolated from one another in the sense that either input is matched no matter what is connected to the other input. Thus, both common- and differential-mode signals are simultaneously matched, and the common-mode rejection (CMR) is made independent of the source reflection coefficient. (However, as will be brought out below, it is important that the inputs be exactly similar if the CMR is not to be impaired.) Also, CMR is theoretically frequency-independent. Consider that the inductance introduced by the toroidal cores falls across R4, the load, and attenuates the output below some frequency. However, if R1 and R3 have the same value, common-mode will still be rejected. That is, both common- and differential-mode signals will be attenuated together so that the CMR is not impaired.

The implementation of the baluns in the transmitter is shown in figures 7 and 8. One of the ferrite-covered floating input lines is at the top of

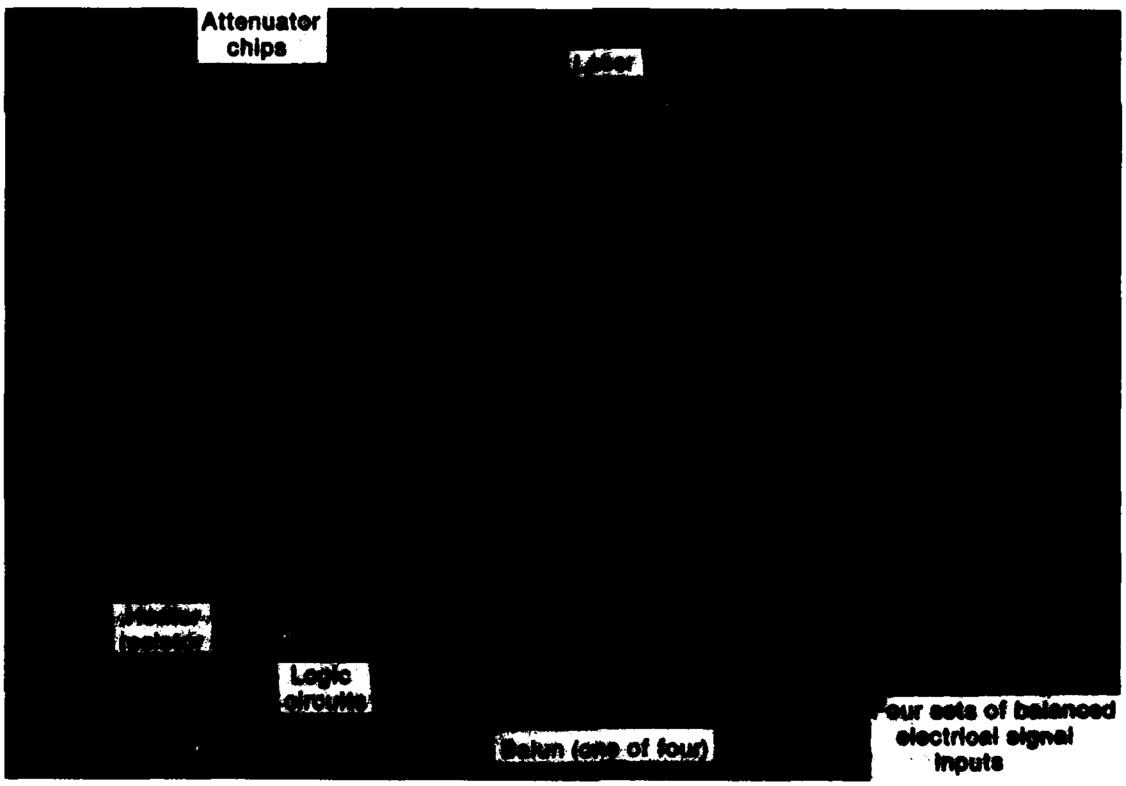

Figure 7. Side view of remote signal transmitter. Baluns are visible extending lengthwise at bottom.

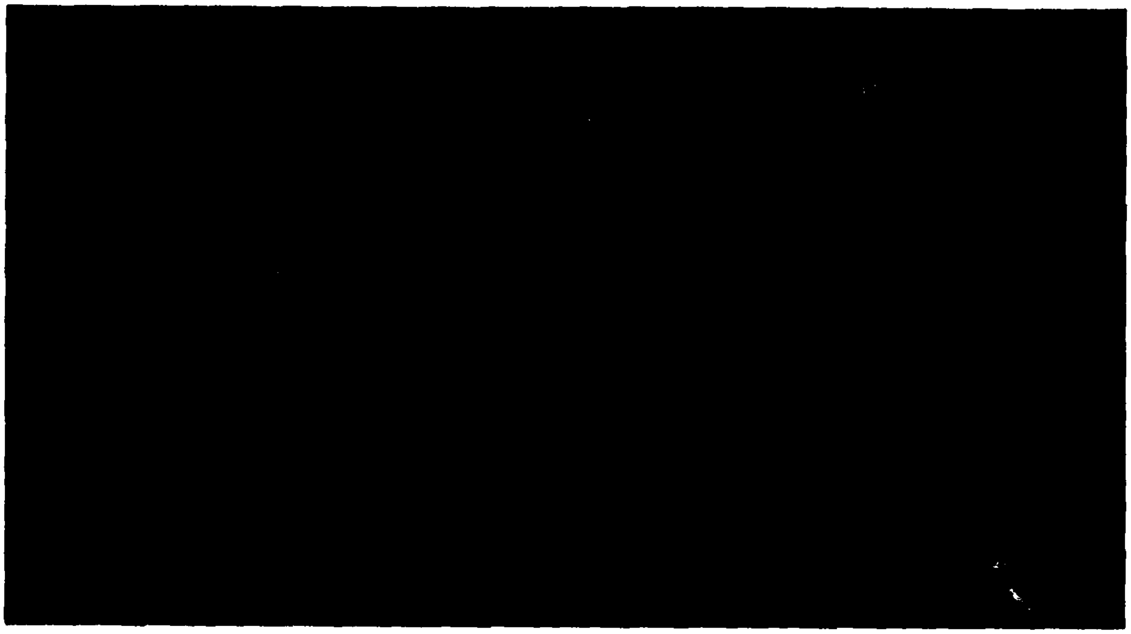

Figure 8. End of balun assembly showing resistor bridges and selector relays. One balun and one relay not assembled in this view.

the lower section of the transmitter, and its fellow nonfloating line is immediately below it. One end of each line is connected to an input SMA connector and the other ends are tied together by the bridge resistors. Figure 8 shows that the resistors are attached to the circuit by vanishingly short leads. Precise performance measurements of the completed baluns[2] show that the resistors were not unbalanced by soldering heat.

The circular cans of figure 8 are two of the three TO-5 relays in the selector tree. The microstrip interconnecting the baluns and relays is on the opposite side of the board and not visible. The board was photographed when partially completed and empty holes are seen at the locations of one bridge assembly and one relay.

To eliminate cross-talk between neighboring baluns it was necessary to install conducting shields between units. One of the shielding plates is visible behind the row of cores in figure 7. Similar shield plates are located between each set of cores and also (not visible) above and below the cores.

2.2 *Attenuator and Calibrator*

The signal which has been selected passes next to the four-stage attenuator. As shown in figure 9, each stage comprises a double-pole double throw (dpdt) magnetic latching relay and a thick-film attenuator pad of appropriate value. Minimizing the size of the attenuators is, of course, very beneficial in obviating system-generated EMP (SGEMP) problems,[3] as well as being desirable, per se. The attenuator chips are soldered directly to the relay lead wires and can be seen at the lower left of the analog circuit board, figure 10. The relays are at the upper left corner of figure 11.

The calibration waveform generator consists of a clock oscillator and a Johnson counter made of Schottky transistor-transistor (TTL) logic (U2 and U3, fig. 9). These two dual in-line packages

[2] *Jonathan Vanderwall, An Improved Balun for the SXTF Fiber Optics Link, Proceedings of the Fiber Optics in the Nuclear Environment Symposium Harry Diamor Laboratories, March 1980, Vol II, Radiation f 'sics (DNA P-2).*

[3] *James C. Blackburn and Alan Bromborsky, The Construction and Analysis of a Hardened Analog Fiber Optic Data Link, IEEE Trans. Nucl. Sci.,* **NS-24**, *6 (December 1977).*

(DIP's) are visible in figure 11. The counter outputs are resistively summed to produce a rectangular, bipolar calibrating waveform. The wavefrom first goes positive, then to zero, then negative, then returns to zero with a clock rate of approximately 20 MHz and rise/fall times of about 5 ns. Note that the calibrator waveform is inserted after the 24-dB attenuator, but before the remaining stages. During calibration, the 24-dB attenuator is inserted to provide isolation from the inputs. The calibration amplitude can then be varied by changing the remaining attenuators, thus providing a good test of the system linearity. When the calibrator is not operating, the 1800-ohm resistor (R6) is an insignificant perturbation of the 50-ohm microstrip.

2.3 *Amplifiers and Equalization*

The amplifiers U4 and U5 (fig. 9) are visible at the center top of figure 11. They are commercial hybrid units which provide an overall gain of about 22 dB. The upper cutoff frequency is conservatively specified as 1 GHz. Lower cutoff is set by the coupling capacitors in the kilohertz range, but system low-frequency cutoff is in fact established near 12 kHz by the baluns. An equalizing network (C12, R15, etc) couples the amplifier to the laser and compensates for various circuit imperfections, chiefly "dribble-up," incurred in the small diameter balun coax and in the microstrip of the input selector and attenuator. CR6 prevents a power-on surge from reaching the laser.

The gain of the two-stage amplifier is sufficient that an input signal of about 1 mV will produce a 1:1 signal-to-noise ratio at the receiver output. Additional gain stages could readily be added to decrease the low-signal capability, but nuclear radiation hardness would be decreased. The system as shown was a good compromise for the test requirements.

2.4 *Laser, Laser Bias Stabilization, and Dither Oscillator*

Possibly the most far-reaching decision in the construction of this link was in the selection of the laser diode. To save power, we required a low lasing threshold current and high differential quantum efficiency. To achieve an adequate dynamic range, we required low distortion products and therefore a highly linear response to modulation. The Mitsubishi unit specified appears to meet these objectives satisfactorily, although laser diodes made by Hitachi, General Optronics, or others, may conceivably be used. The disadvantage of the laser selected is its high coherence, which tends to incur modal noise.[4]

The proper bias point for the laser is a strong function of temperature and must be adjusted even for small temperature variations as well as for aging effects. In the transmitter this is arranged by a feedback loop. The front facet of the laser illuminates the fiber. The back facet illuminates a PIN photodiode, producing a proportional photocurrent. The laser and its output fiber pigtail are readily distinguished in figure 10. The PIN photodiode is contained within the brass block to which the laser is attached. This current is compared to a reference, amplified, and fed back to the laser in such a fashion as to hold the steady-state optical output constant. Since the PIN diode, CR4, is an excellent current source, the drop across R28 is a function only of laser intensity. This drop is compared by Q4 to the voltage established by zener CR3, and the result amplified by Q2 and applied to the laser. An operational amplifier, with its high gain, was avoided to lessen nuclear radiation response.

An additional modulating bias signal is applied to the laser diode. This is a continous wave (cw) signal of about 1.5 or 2 GHz, well outside the link passband. This signal modulates the laser both in amplitude and wavelength, reducing its coherence time and also decorrelating its instantaneous wavelength, which otherwise tends to be a function of the signal transmitted. This greatly reduces the modal noise.[5] The source of the cw signal, a commercially available hybrid oscillator, is coupled to the laser by a resistor capacitor (RC)

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[4]*R. E. Epworth, The Phenomenon of Modal Noise in Fiber Systems, Proceedings of the 9th European Conference on Optical Communication, Genoa, Italy (1978).*

[4]*R. E. Epworth, The Phenomenon of Modal Noise in Fiber Systems, Proceedings of the 9th European Conference on Optical Communication, Genoa, Italy (1978).*

[5]*Jonathan Vanderwall and James C. Blackburn, Suppression of Some Artifacts of Modal Noise in Fiber Optic Systems, Optics Letters, 4, 9 (September 1979) 295-296.*

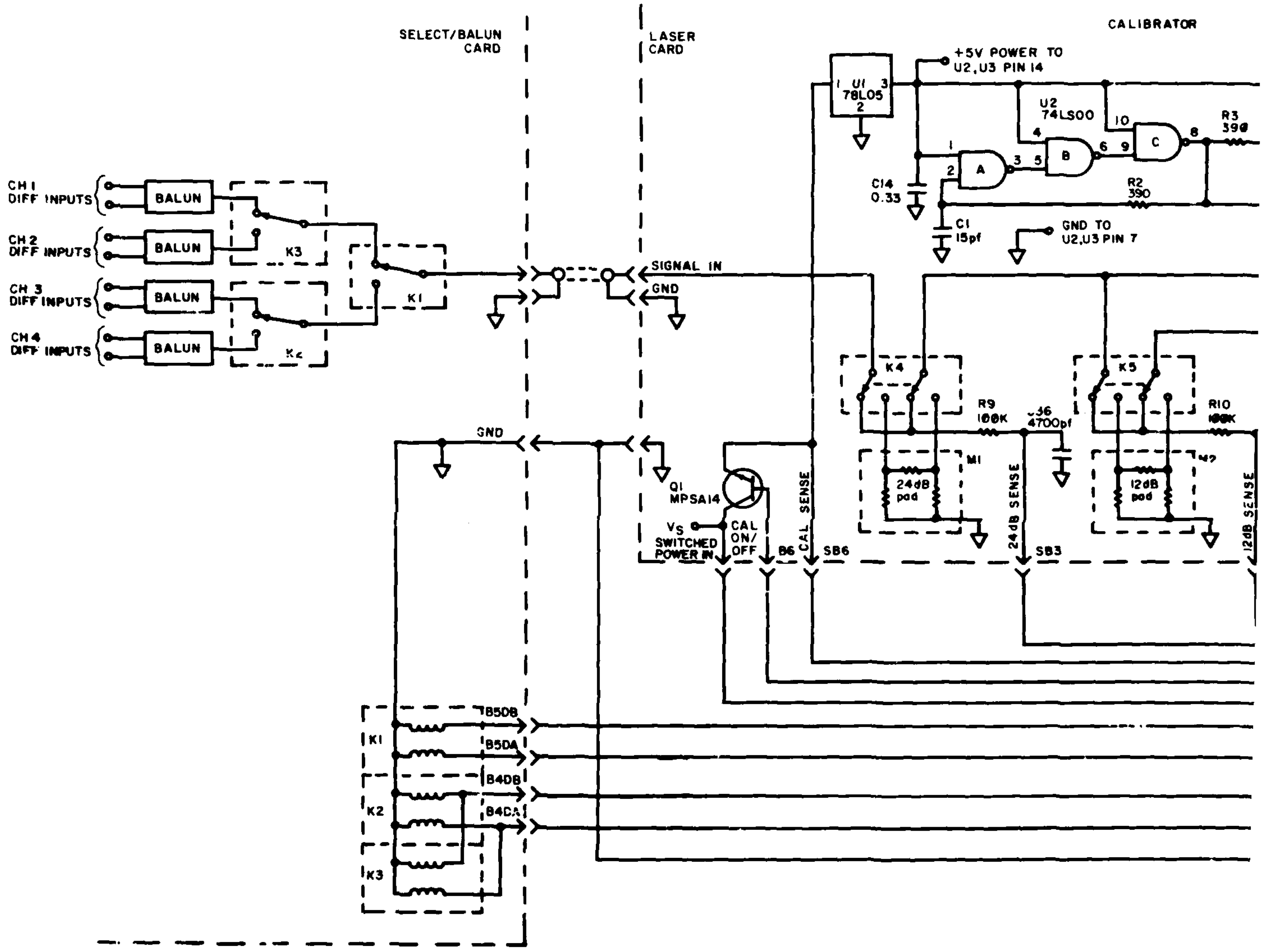
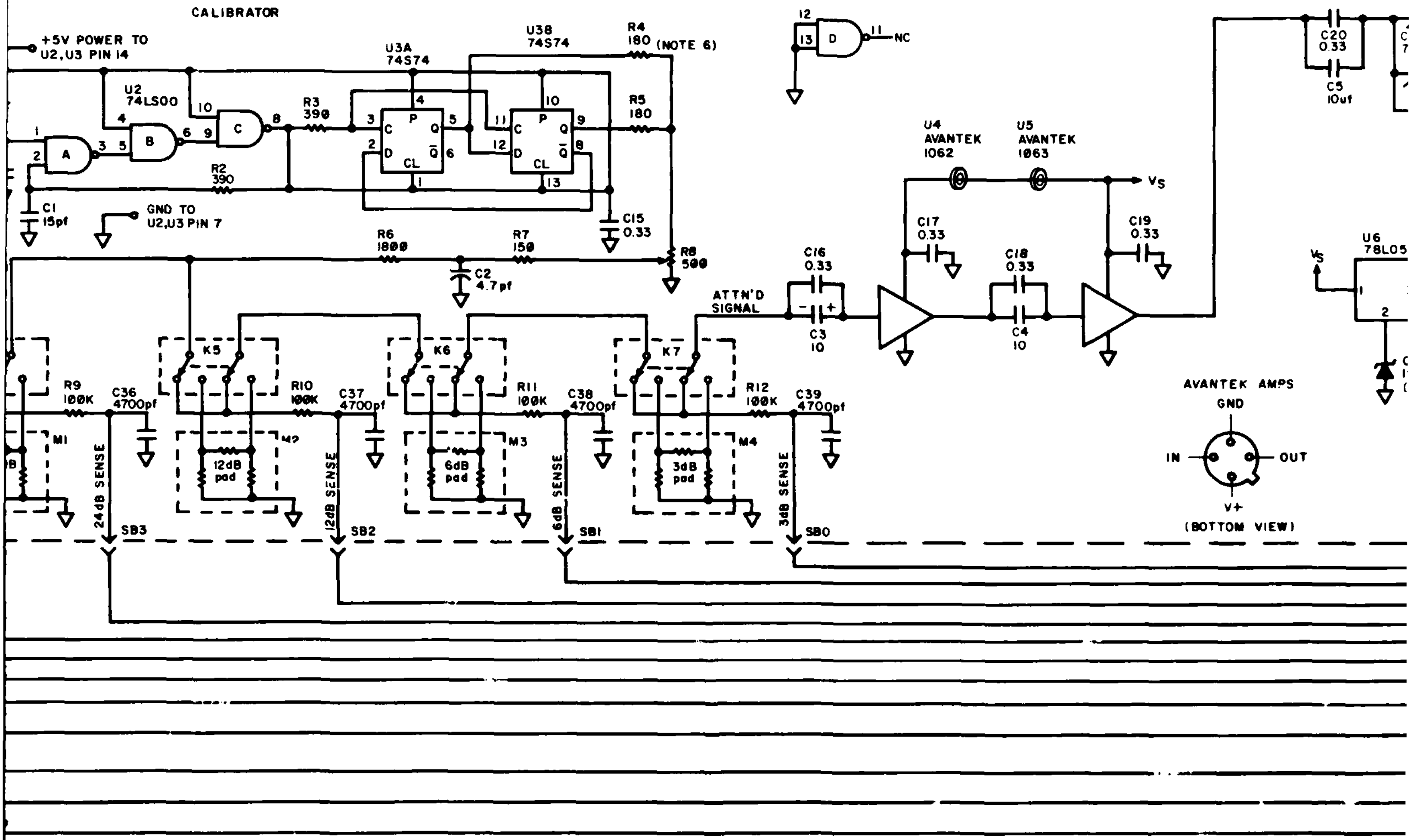
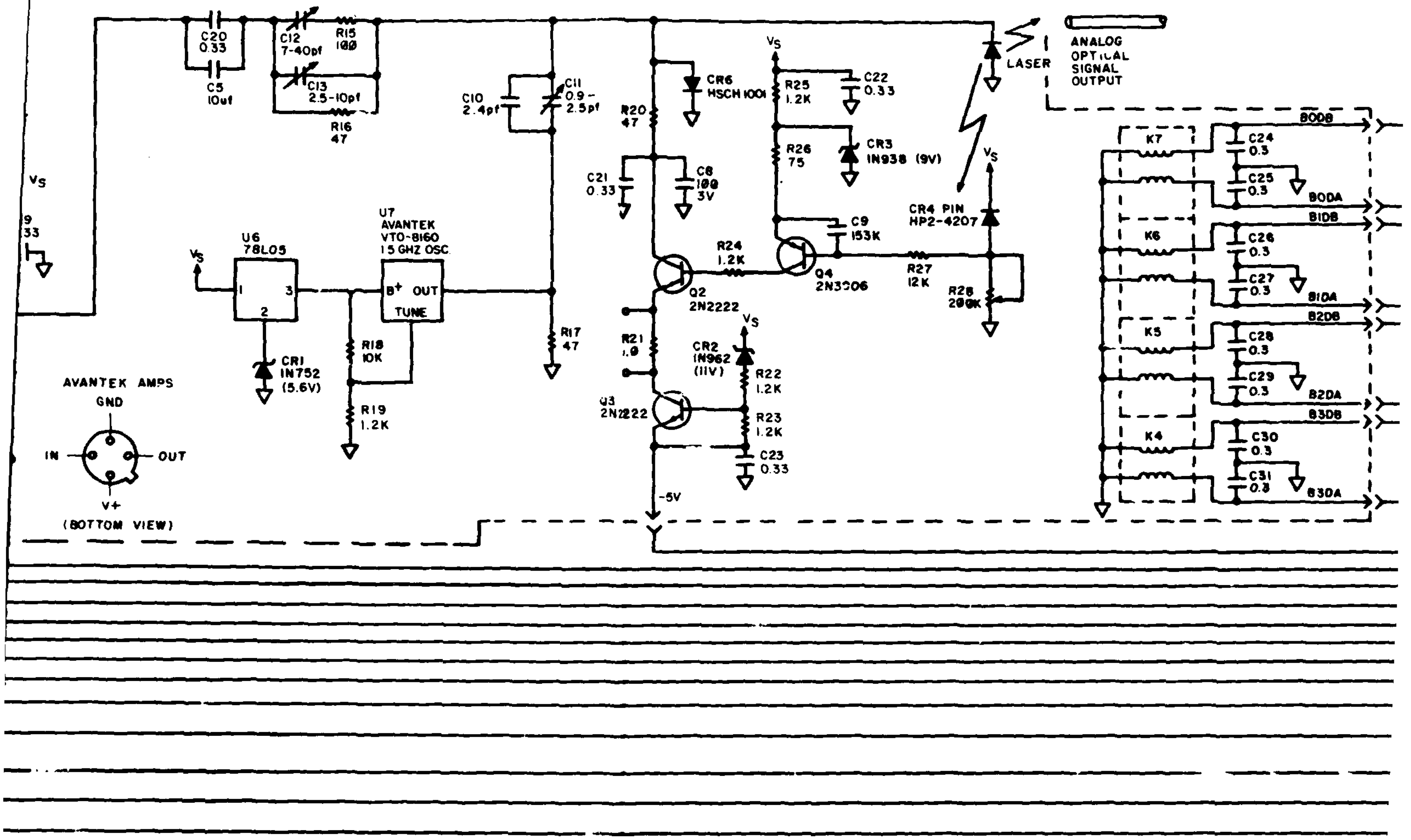


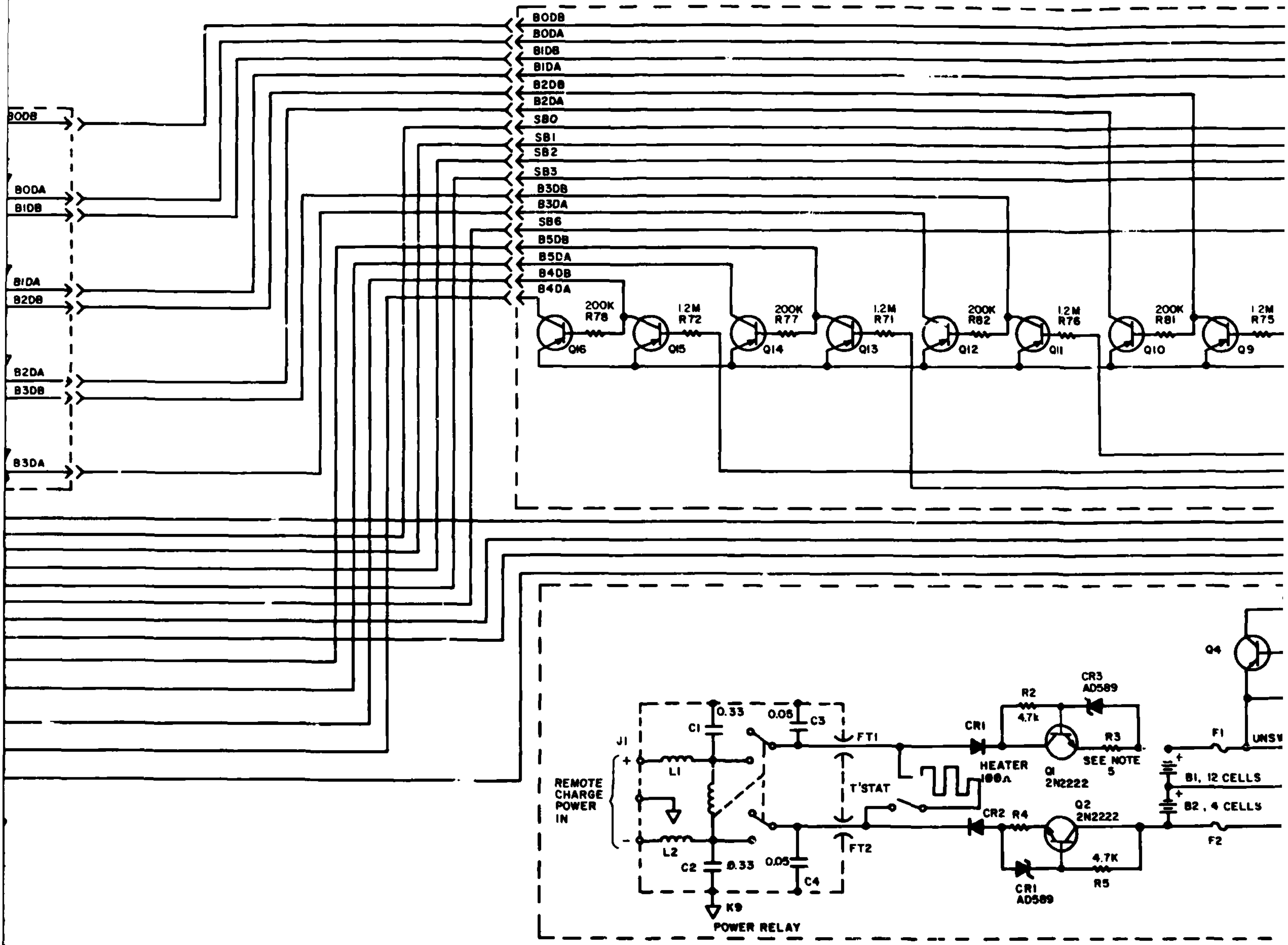
Figure 9. Schematic of remote signal transmitter. Note that circuitry is subdivided into four sections for discussion.

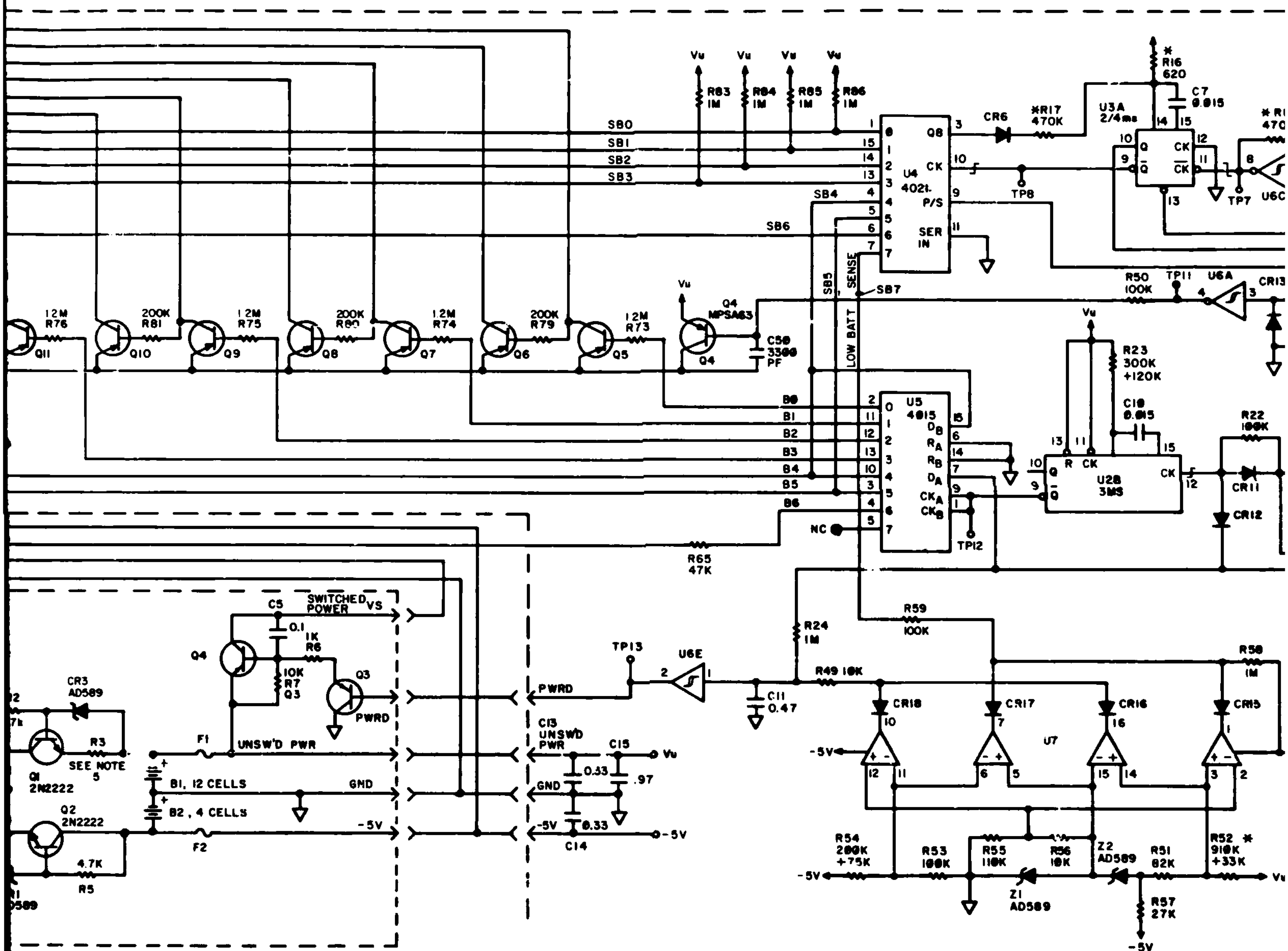
1



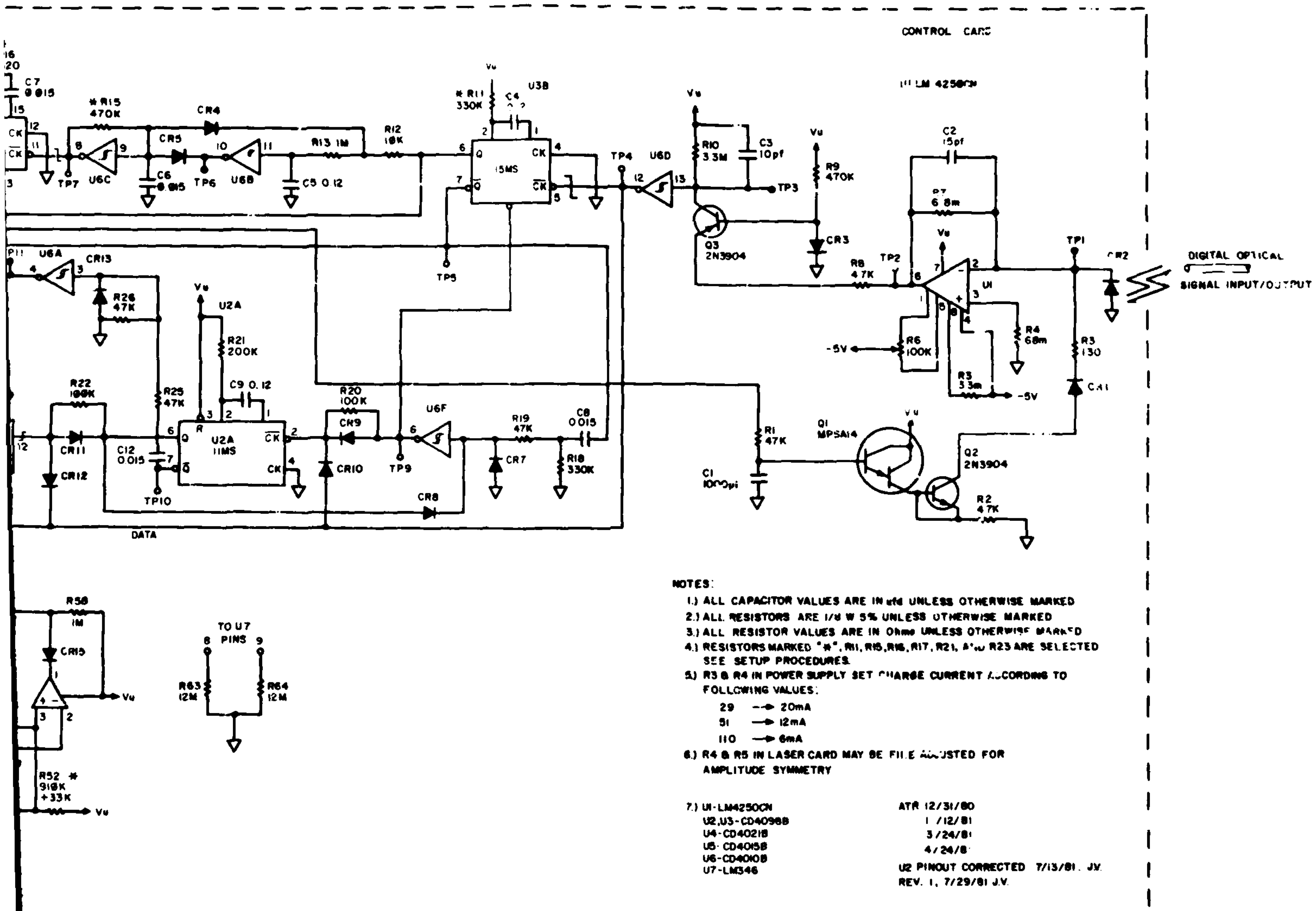
CALIBRATOR
+5V POWER TO U2,U3 PIN 14
U2 74LS00
U3A 74S74
U3B 74S74
R4 180 (NOTE 6)
R5 180
R3 390
R2 390
C1 15pf
GND TO U2,U3 PIN 7
C15 0.33
R6 1800
R7 150
R8 500
C2 4.7pf
ATTN'D SIGNAL
C16 0.33
C3 10
U4 AVANTEK 1062
U5 AVANTEK 1063
VS
C17 0.33
C18 0.33
C4 10
C19 0.33
C20 0.33
C5 10uf
U6 78L05
NC
K5
K6
K7
R9 100K
C36 4700pf
R10 100K
C37 4700pf
R11 100K
C38 4700pf
R12 100K
C39 4700pf
M1
M2
M3
M4
12dB pad
6dB pad
3dB pad
24dB SENSE
12dB SENSE
6dB SENSE
3dB SENSE
SB3
SB2
SB1
SB0
AVANTEK AMPS
GND
IN
OUT
V+
(BOTTOM VIEW)


C20
0.33
C5
10uf
C12
7-40pf
R15
100
C13
2.5-10pf
R16
47
C10
2.4pf
C11
0.9-
2.5pf
R20
47
CR6
HSCH 1001
Vs
R25
1.2K
C22
0.33
LASER
ANALOG
OPTICAL
SIGNAL
OUTPUT
R26
75
CR3
1N938 (9V)
C21
0.33
C8
100
3V
CR4 PIN
HP2-4207
C9
153K
R24
1.2K
Q4
2N3906
R27
12K
R28
200K
Q2
2N2222
U6
78L05
U7
AVANTEK
VTO-8160
1.5 GHZ OSC.
B+ OUT
TUNE
R17
47
R21
1.9
CR2
1N962
(11V)
R22
1.2K
R23
1.2K
C23
0.33
Q3
2N2222
-5V
CR1
1N752
(5.6V)
R18
10K
R19
1.2K
AVANTEK AMPS
GND
IN
OUT
V+
(BOTTOM VIEW)
K7
K6
K5
K4
C24
0.3
C25
0.3
C26
0.3
C27
0.3
C28
0.3
C29
0.3
C30
0.3
C31
0.3
B0DB
B0DA
B1DB
B1DA
B2DB
B2DA
B3DB
B3DA


B0DB
B0DA
B1DB
B1DA
B2DB
B2DA
SB0
SB1
SB2
SB3
B3DB
B3DA
SB6
B5DB
B5DA
B4DB
B4DA
200K R78
1.2M R72
Q16
Q15
200K R77
1.2M R71
Q14
Q13
200K R82
1.2M R76
Q12
Q11
200K R81
1.2M R75
Q10
Q9
Q4
CR3 AD589
R2 4.7k
CR1
R3
SEE NOTE 5
Q1 2N2222
HEATER 100Ω
F1
UNSW
B1, 12 CELLS
B2, 4 CELLS
F2
J1
REMOTE CHARGE POWER IN
C1
0.33
0.05
C3
FT1
L1
T'STAT
L2
C2
0.33
0.05
C4
FT2
CR2
R4
Q2 2N2222
4.7K
R5
CR1 AD589
K9
POWER RELAY



Vu
R83 1M
R84 1M
R85 1M
R86 1M
SB0
SB1
SB2
SB3
SB4
SB6
SB5
SENSE
SB7
LOW BATT
U4 4021
Q8
CK
P/S
SER IN
CR6
*R17 470K
TP8
*R16 620
C7 0.015
U3A 2/4ms
TP7
U6C
R50 100K
TP11
U6A
CR13
12M R76
Q11
200K R81
Q10
12M R75
Q9
200K R80
Q8
12M R74
Q7
200K R79
Q6
12M R73
Q5
Q4 MPSA63
C50 3300 PF
R23 300K +120K
C10 0.015
R22 100K
U5 4015
B0
B1
B2
B3
B4
B5
B6
NC
U28 3MS
CR11
CR12
TP12
R65 47K
R59 100K
R24 1M
C5
SWITCHED POWER
VS
0.1
1K R6
10K R7 Q3
Q4
Q3
PWRD
CR3 AD589
R3
SEE NOTE 5
Q1 2N2222
Q2 2N2222
4.7K R5
F1
UNSW'D PWR
B1, 12 CELLS
GND
B2, 4 CELLS
-5V
F2
TP13
U6E
C11 0.47
R49 10K
CR18
CR17
CR16
CR15
R58 1M
U7
C13 UNSW'D PWR
C15
0.33
.97
0.33
C14
R54 200K +75K
R53 100K
R55 110K
R56 10K
Z1 AD589
Z2 AD589
R51 82K
R52 * 910K +33K
R57 27K



NOTES:

1.) ALL CAPACITOR VALUES ARE IN ufd UNLESS OTHERWISE MARKED
2.) ALL RESISTORS ARE 1/4 W 5% UNLESS OTHERWISE MARKED
3.) ALL RESISTOR VALUES ARE IN Ohms UNLESS OTHERWISE MARKED
4.) RESISTORS MARKED "*", R11, R15, R16, R17, R21, AND R23 ARE SELECTED SEE SETUP PROCEDURES.
5.) R3 & R4 IN POWER SUPPLY SET CHARGE CURRENT ACCORDING TO FOLLOWING VALUES:
    29 → 20mA
    51 → 12mA
    110 → 6mA
6.) R4 & R5 IN LASER CARD MAY BE FILE ADJUSTED FOR AMPLITUDE SYMMETRY

7.) U1-LM4250CN
    U2,U3-CD4098B
    U4-CD4021B
    U5-CD4015B
    U6-CD4010B
    U7-LM346

ATR 12/31/80
1/12/81
3/24/81
4/24/81
U2 PINOUT CORRECTED 7/13/81. J.V.
REV. 1, 7/29/81 J.V.

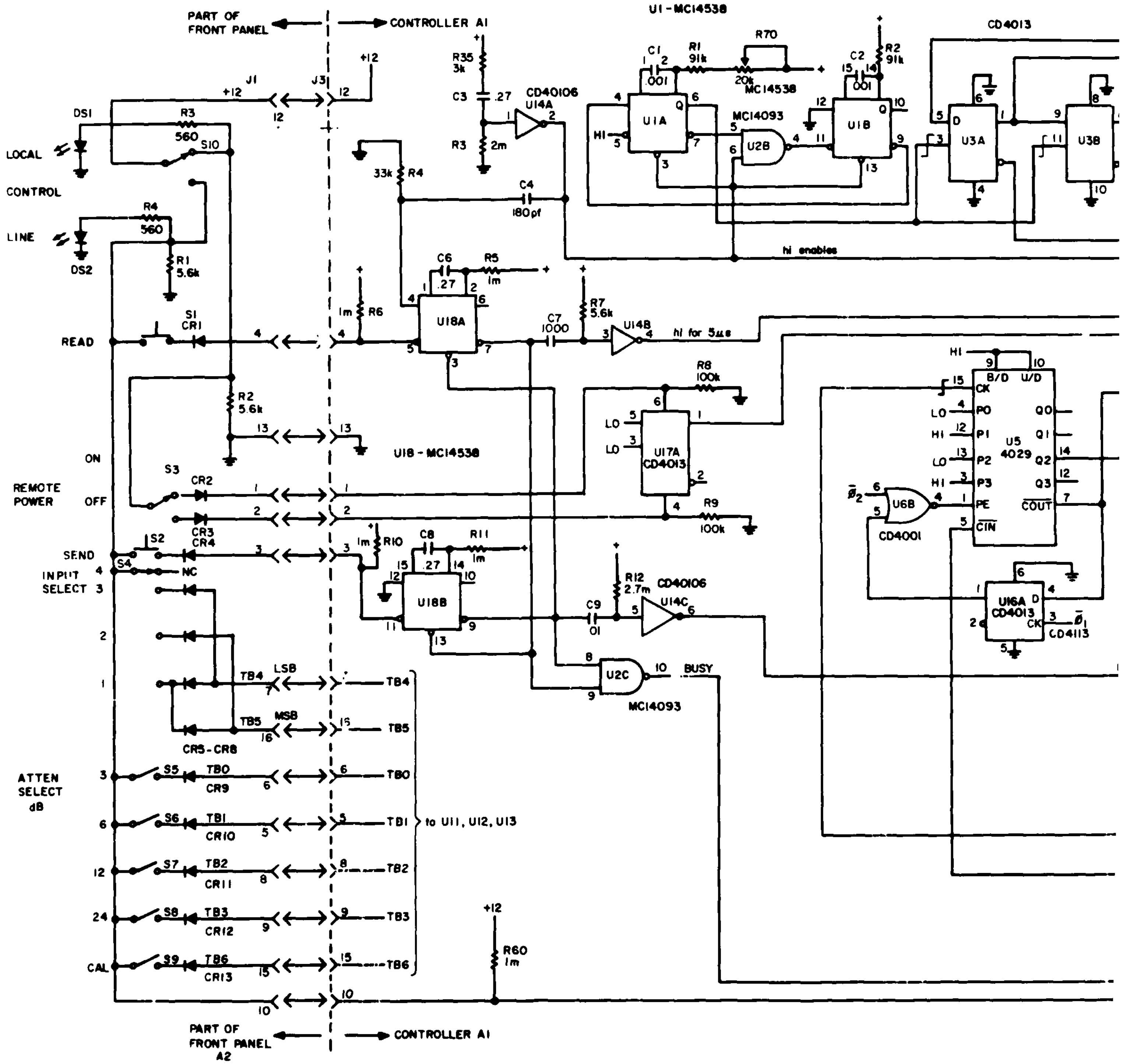


Figure 13. Schematic diagram of controller. Operator commands and monitor functions are optically transmitted/received here.

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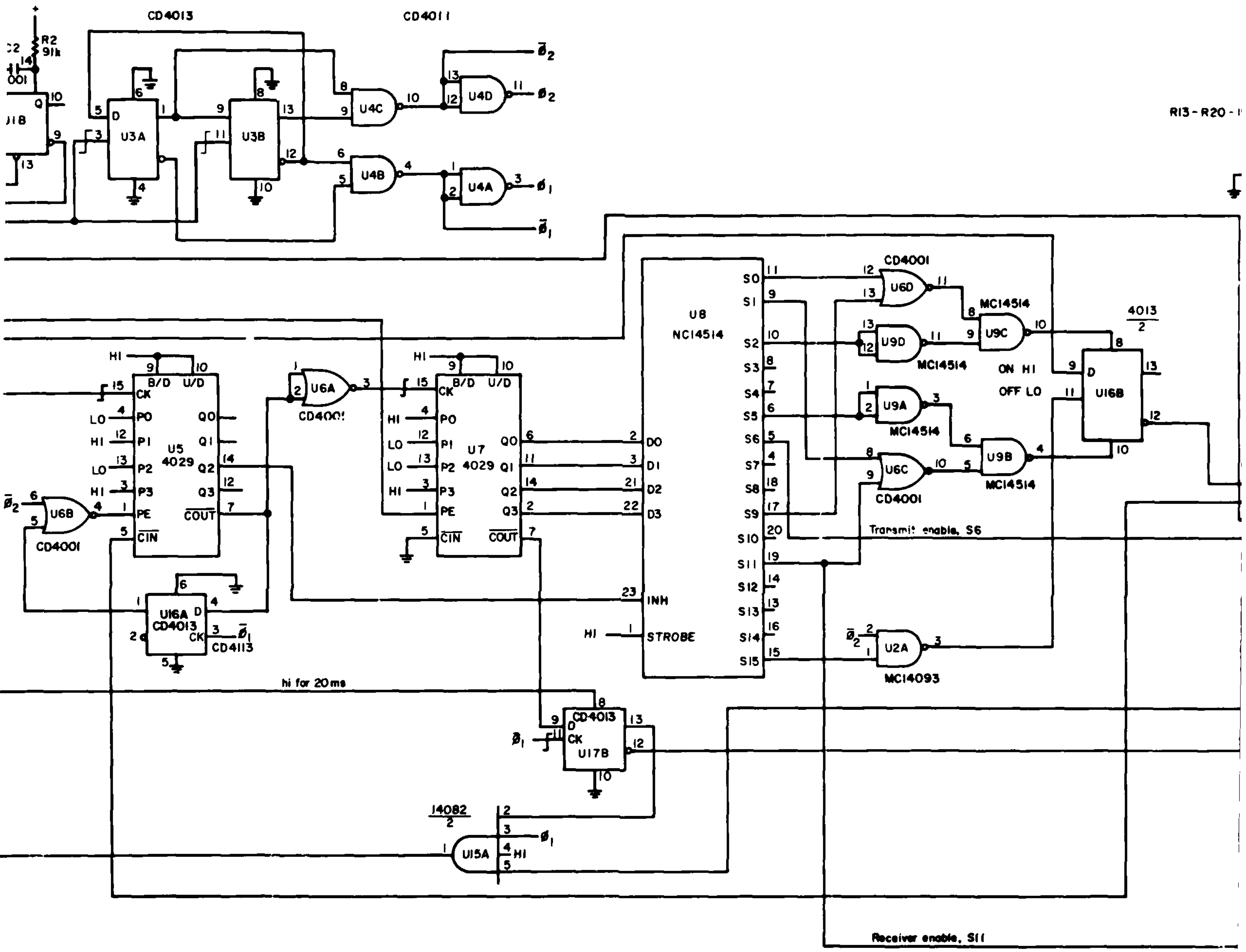
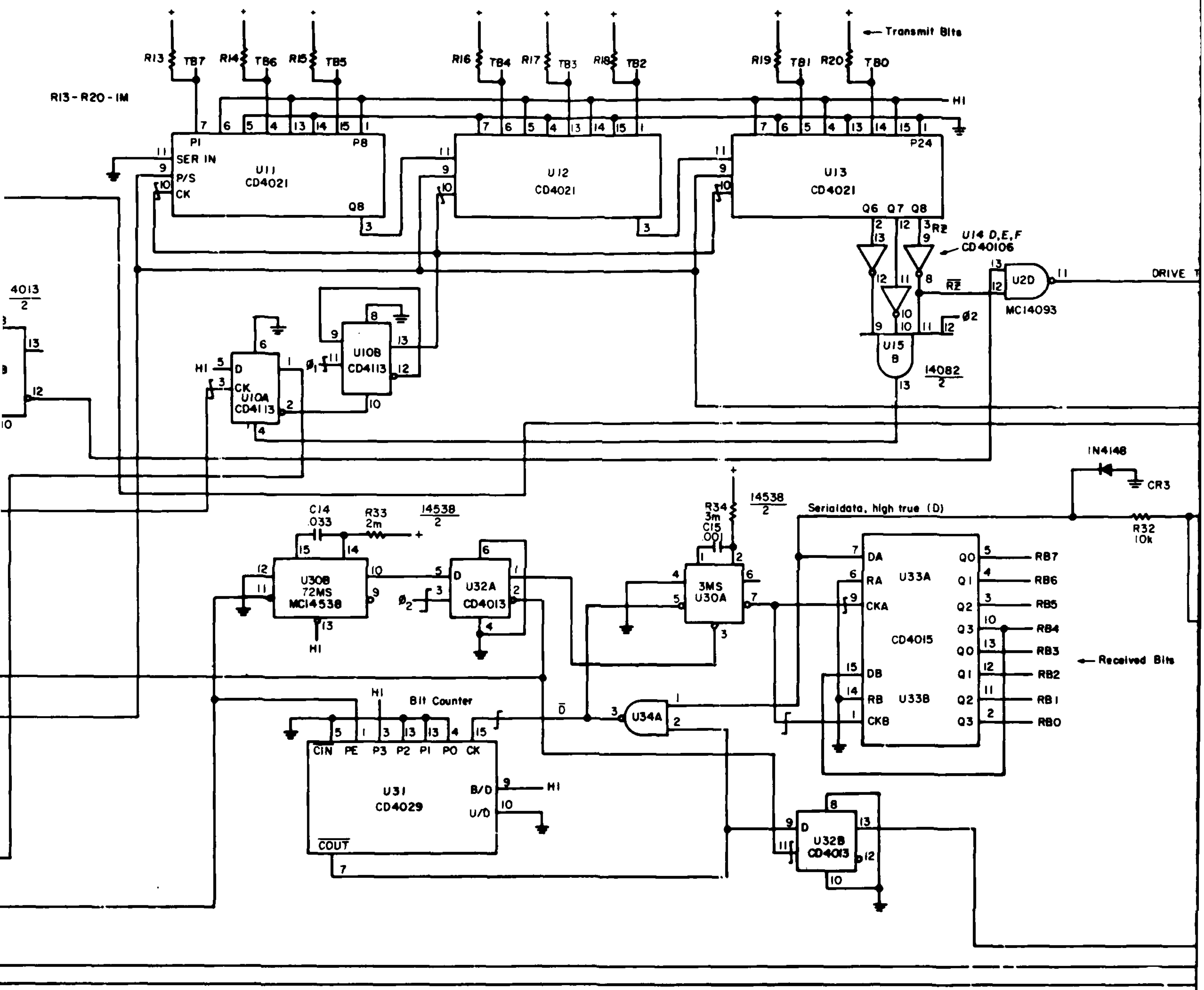
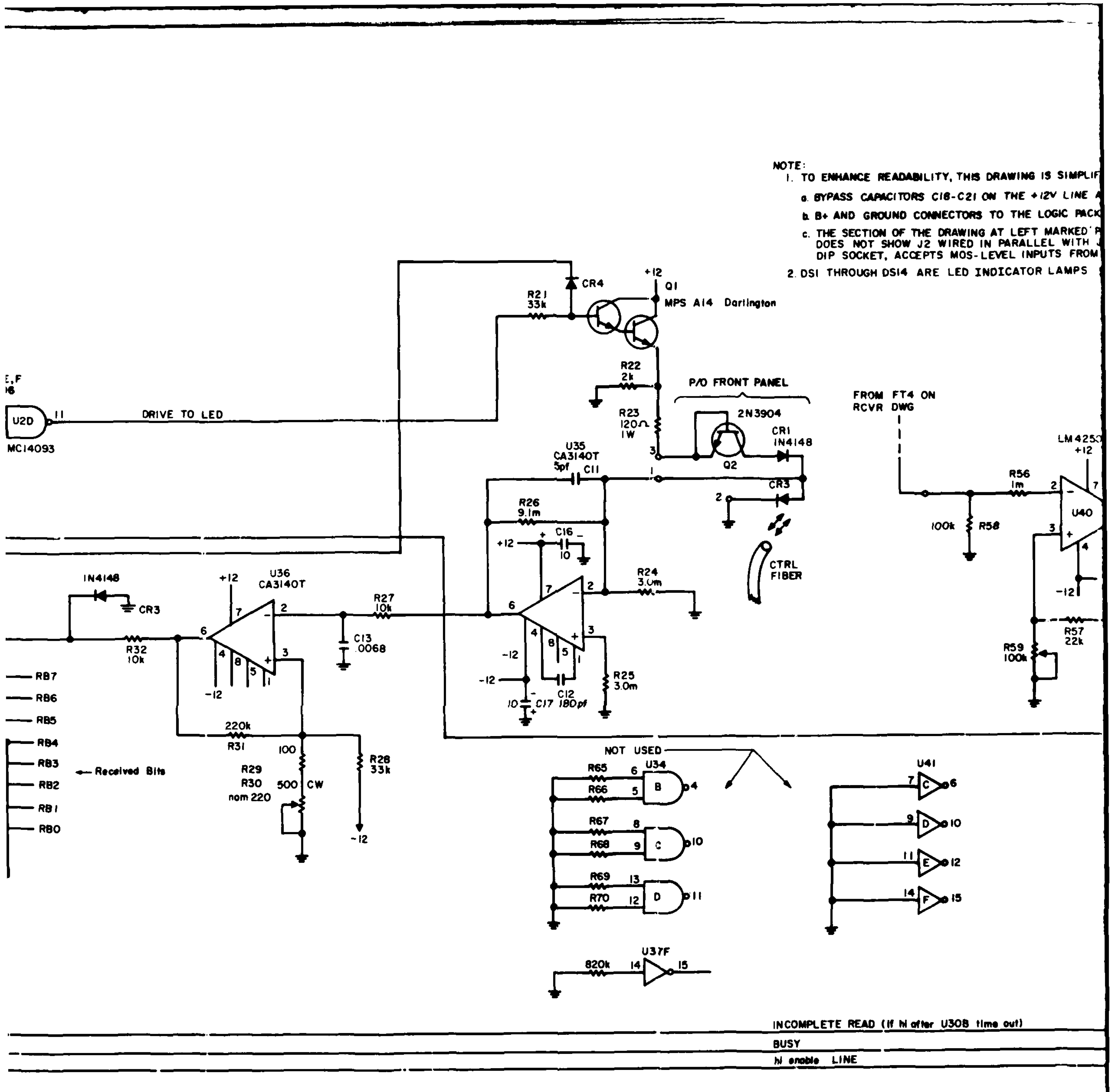


CD4013
CD4011
R2 91k
U1B
U3A
U3B
U4C
U4D
U4B
U4A
R13 - R20 -
U8
NC14514
U5
4029
U7
4029
U6A
CD4001
U6B
CD4001
U16A
CD4013
CD4113
U6D
U9D
MC14514
U9C
ON HI
OFF LO
4013
2
U16B
U9A
MC14514
U9B
MC14514
U6C
CD4001
Transmit enable, S6
U2A
MC14093
STROBE
INH
hi for 20ms
CD4013
U17B
J4082
2
U15A
Receiver enable, S11



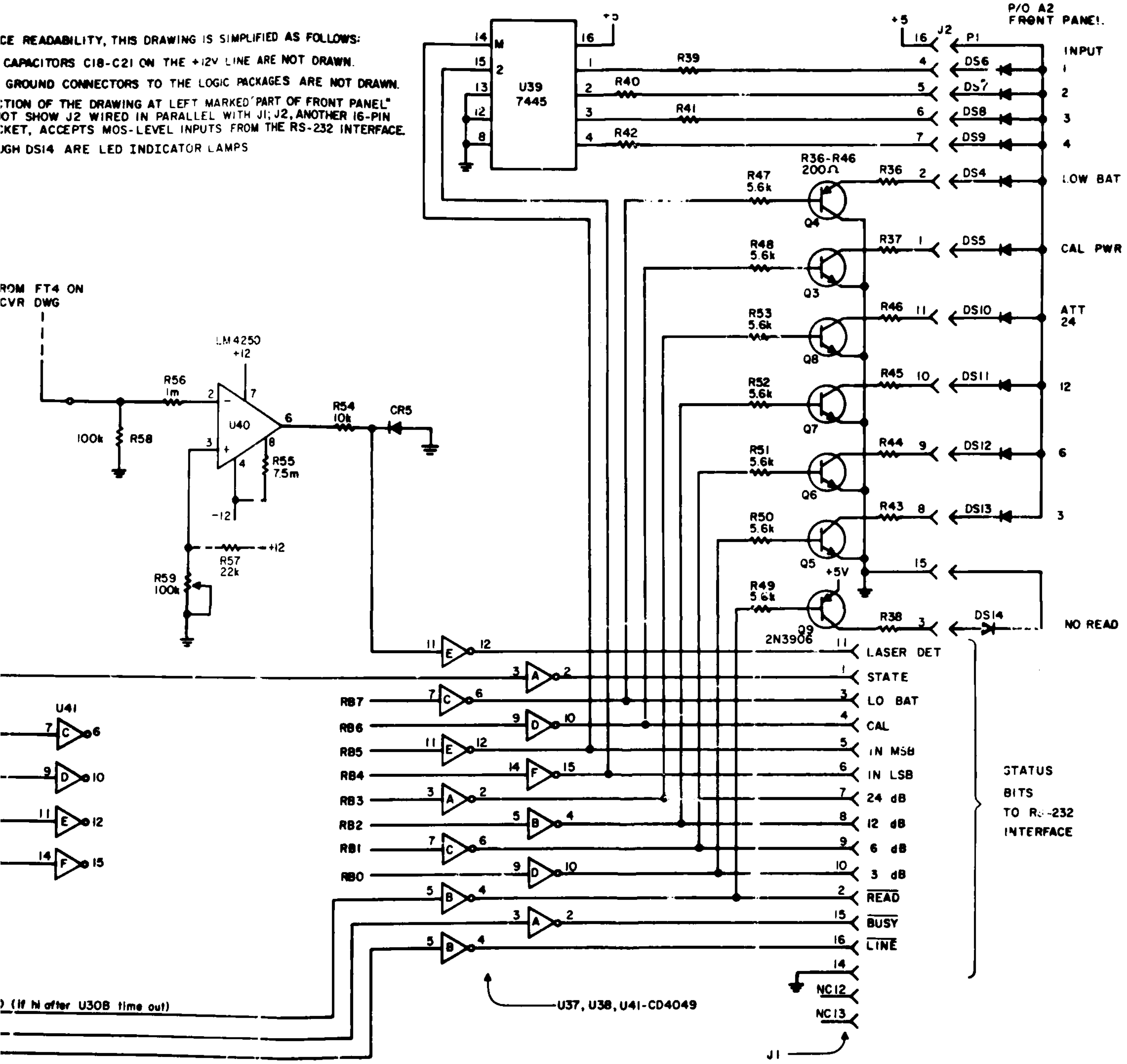
Transmit Bits
R13 TB7 R14 TB6 R15 TB5 R16 TB4 R17 TB3 R18 TB2 R19 TB1 R20 TB0
R13-R20-1M
HI
U11 CD4021
U12 CD4021
U13 CD4021
U14 D,E,F CD40106
U2D MC14093
DRIVE
U10A CD4113
U10B CD4113
U15 B
14082/2
4013/2
1N4148
CR3
R32 10k
C14 .033
R33 2m
14538/2
R34 3m
C15 .001
U30B 72MS MC14538
U32A CD4013
3MS U30A
Serialdata, high true (D)
U33A CD4015 U33B
RB7 RB6 RB5 RB4 RB3 RB2 RB1 RB0
Received Bits
Bit Counter
U31 CD4029
U34A
U32B CD4013



NOTE:
1. TO ENHANCE READABILITY, THIS DRAWING IS SIMPLIF
a. BYPASS CAPACITORS C18-C21 ON THE +12V LINE A
b. B+ AND GROUND CONNECTORS TO THE LOGIC PACK
c. THE SECTION OF THE DRAWING AT LEFT MARKED P DOES NOT SHOW J2 WIRED IN PARALLEL WITH J DIP SOCKET, ACCEPTS MOS-LEVEL INPUTS FROM
2. DS1 THROUGH DS14 ARE LED INDICATOR LAMPS
CR4
+12
Q1
MPS A14 Darlington
R21 33k
R22 2k
P/O FRONT PANEL
R23 120Ω 1W
2N3904
CR1 1N4148
Q2
CR3
CTRL FIBER
FROM FT4 ON RCVR DWG
LM4250
U2D
MC14093
DRIVE TO LED
U35 CA3140T
5pf C11
R26 9.1m
C16 10
R24 3.0m
R25 3.0m
C12 180pf
C17 10
1N4148
CR3
U36 CA3140T
R32 10k
R27 10k
C13 .0068
220k R31
R29 R30 nom 220
100
500 CW
R28 33k
-12
RB7
RB6
RB5
RB4
RB3
RB2
RB1
RB0
Received Bits
R56 1m
100k R58
U40
R57 22k
R59 100k
NOT USED
R65 R66 U34 B
R67 R68 C
R69 R70 D
U41 C D E F
820k U37F
INCOMPLETE READ (if hi after U308 time out)
BUSY
hi enable LINE

3

CE READABILITY, THIS DRAWING IS SIMPLIFIED AS FOLLOWS:
CAPACITORS C18-C21 ON THE +12V LINE ARE NOT DRAWN.
GROUND CONNECTORS TO THE LOGIC PACKAGES ARE NOT DRAWN.
:TION OF THE DRAWING AT LEFT MARKED 'PART OF FRONT PANEL"
OT SHOW J2 WIRED IN PARALLEL WITH J1; J2, ANOTHER 16-PIN
:KET, ACCEPTS MOS-LEVEL INPUTS FROM THE RS-232 INTERFACE.
JGH DS14 ARE LED INDICATOR LAMPS



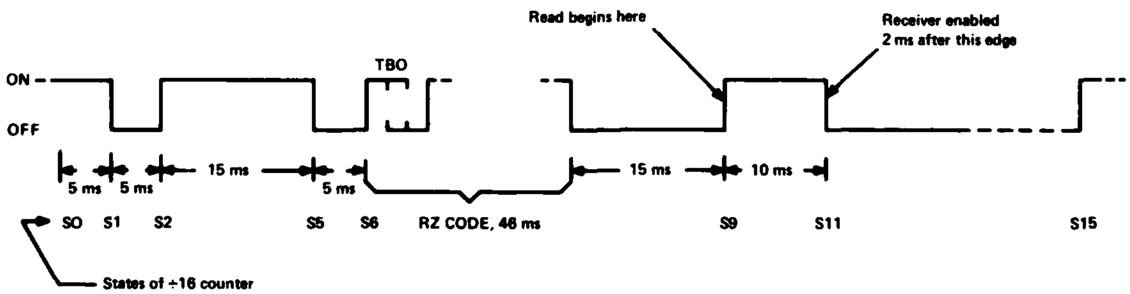
retransmit clock is halted in one of two possible ways. If the remote power is commanded ON, the controller LED will reilluminate CR2, and DATA will consequently be held true. This halts the retriggering of U3B, and when that circuit times out the oscillator U6C will be disabled. Alternatively, if the illumination of CR2 is not resumed by reason of an OFF command from the controller, the retransmit clock must be halted to prevent running down the battery. This occurs when the delay generator comprising R13, C5, and U6B times out and the output of U6B drops, pulling down the input to U6C via CR5, thus inhibiting the retransmit clock. Note that this is also a fail-safe provision against the possibility of a broken control fiber or failure of the controller power.

Operation of the READ cycle is straightforward, but the action of the circuit in response to a SEND command is decidedly less so. It is best to begin with the waveform representing the light incident on CR2 from the controller LED. This is shown in figure 14 and in somewhat more detail in figure 15, which represents waveforms at some test points on the control card. Suppose that the controller LED is initially on as it will be if remote power is "ON." Upon initiation of the "SEND" it is turned off for 5 ms, followed by 15 ms on, followed by 5 ms off, followed by the RZ code. The RZ code consists of exactly 8 pulses either 2 or 4 ms wide, at intervals of 6 ms. The longer pulse represents a "1," the shorter, a "0." Turning again to figure 15, let us see how the circuit responds to this waveform.

When DATA, i.e., the output of U6D, first goes low, U3B will be triggered as before and will attempt to initiate a read-back. However, after 5 ms the controller reenergizes its LED, forcing DATA true for 15 ms. Therefore, U3B times out, halting the retransmit clock as described above, and also, via its $\overline{Q}$ connection to C8, R19, CR7, and U6F, generating a low at the output of U6F for some 10 ms. The output of U6F goes low about 3 or 4 ms before DATA again falls, so that U3B is held clear by the low at its reset input and will not be triggered. Moreover, CR9 and CR10 form a low-true AND at the negative-edge trigger input of U2A, the receiver enable one-shot. Thus, when DATA next falls, it triggers U2A, which in turn both enables U2B via CR11 and holds U3B clear via CR8 and U6F.

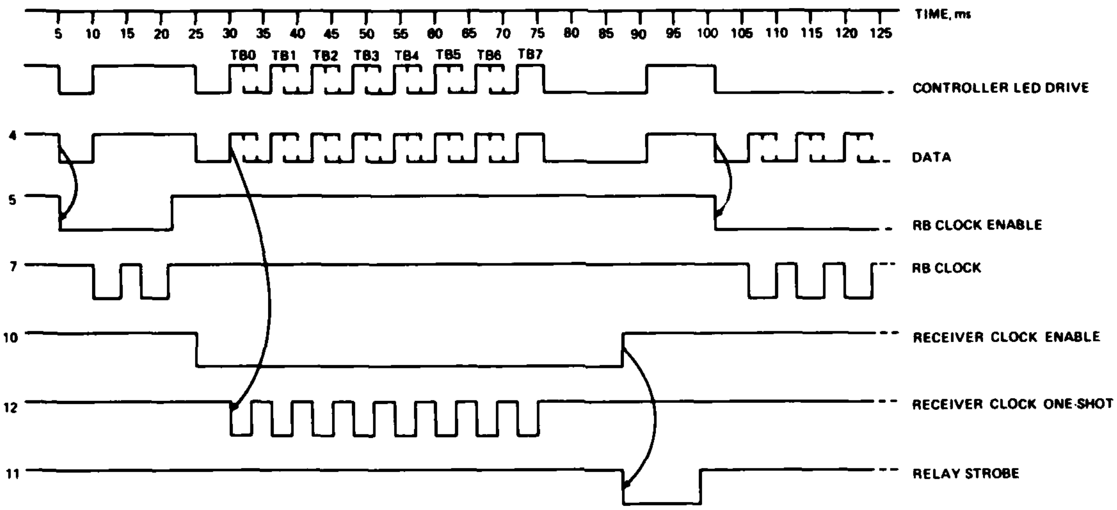
The next rising edge of DATA will be the leading edge of the first bit of the RZ code. This edge triggers U2B, the shift-in monostable. Note the connection of $\overline{DATA}$ to the DATA input of the shift register U5. The $\overline{Q}$ of U2B goes high 3 ms after the leading edge of each of the RZ pulses. A 2-ms-wide pulse is therefore clocked into receiver shift register U5 as a 0, and a 4-ms pulse is clocked in as a 1. This continues until all 8 pulses from the local unit have been received.

Throughout the time that the RZ code is being shifted into the data register in this way, U2A is continually being retriggered by each falling edge of DATA. Thus, U3B is held clear until U2A



LIGHT SIGNAL FROM CONTROLLER LED

Figure 14. Light pulse sequence from controller during communication of command to/from remote transmitter unit.



NOTES: 1. THESE WAVEFORMS WERE DRAWN FROM AN OPERATING CIRCUIT AND ARE THEREFORE NOT IDEALIZED. FOR EXAMPLE, THE RB CLOCK IS SET TO A 7-ms PERIOD, INSTEAD OF THE NOMINAL 8 MS. THIS IS WITHIN TOLERANCE.

2. FOR CONVENIENCE, THE DRIVE WAVEFORM FOR THE CONTROLLER LED IS REPEATED AT THE TOP OF THE DRAWING. THE LAST BIT, TB7, IS NOT USED AND IS ALWAYS 4 ms LONG.

Figure 15. Detailed view of logic timing of remote unit during reception/transmission of command and monitor data.

times out 10 ms after the last falling edge of the RZ code. The receiver is now disabled with the 8 bits stable at the output of U5. A pulse for strobing the data into the latching relays is produced by U6A and associated parts; also, U3B is once again enabled. Observe that the last bit of the RZ code is followed by a 15-ms low, giving sufficient time for all these actions to occur. The controller LED is then taken high for 10 ms, then dropped, initiating the READ sequence described above.

2.6 *Batteries and Charging Circuit*

Transmitter power is furnished by NiCd button cells which have no over-pressure vent and are hence intrinsically vacuum-proof. These cells are accommodated in a compartment attached to the cover. Fully charged cells will power the entire transmitter for approximately 1.5 hrs. Standby time, when only the logic is powered, is a matter of weeks.

The batteries are charged by a front-panel jack. Applying 28 to 32 Vdc to this jack energizes the disconnect relay and powers the charging circuit, shown at lower left, figure 9. When the charging bus is not powered—as during a shot—the relay drops out and disconnects the charging lines from the interior of the transmitter. This circuit is installed partly in a shielded enclosure just behind the charging connector and partly on a printed circuit board mounted vertically behind that. These circuits are at the upper right in figure 16.

The purpose of relay K9 is to decouple the battery-charging links from the transmitter as completely as possible except while charging. As drawn, the decoupling to the case interior is extreme: first, the filters of L1,L2 and C1,C2, then the small (~1 pF) capacitance across the relay contacts, and finally C3,C4 and filter feed-through FT1, FT2. It is possible that it might be more desirable to eliminate C1 and C2 so that the charging cable will not only be decoupled from the transmitter interior, but will also be connected to the transmitter case by only a relatively few picofarads.

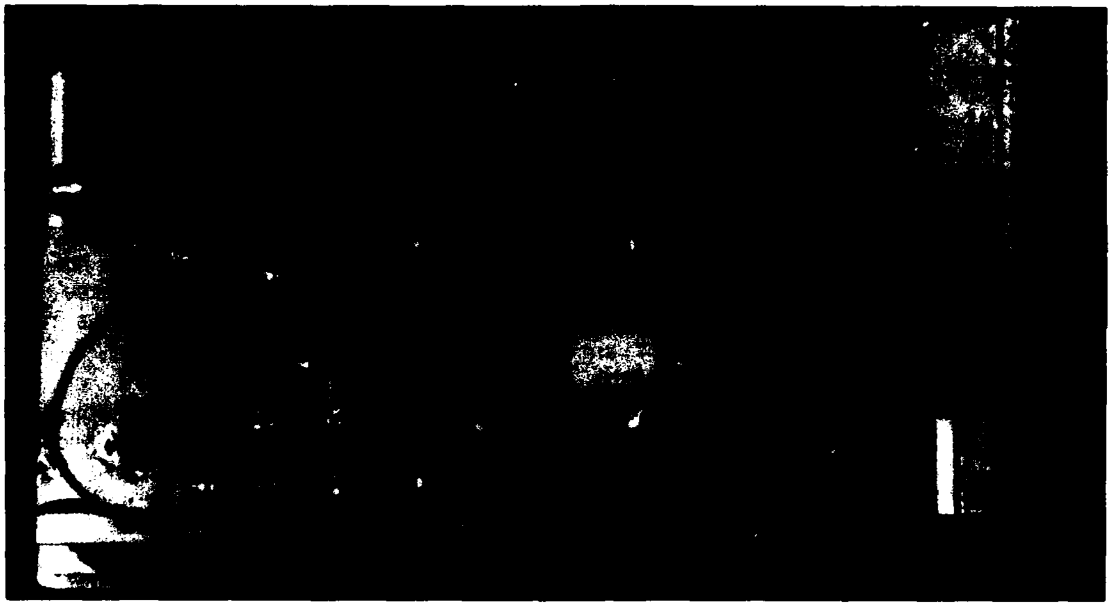


Figure 16. Top view of remote signal transmitter. Shielded enclosure, upper right, is charging decoupler circuit.

Q1, Q2 and associated components form current sources to limit charging to the required 14 hr rate and CR1,CR2 prevent reverse polarity current and battery discharging.

Q3 and Q4 switch the positive power supply in response to the control signals received by detector/LED CR2. The negative supply goes only to the laser circuits and is switched by Q3 (of the laser card) in response to the +15 V supply.

The purpose of the comparator circuitry at the lower right of figure 9 is twofold: it provides the low-battery warning which is sent to the controller by the optical control link and it prevents the transmitter analog circuits from being turned on if the batteries are critically low. The latter is done by crowbarring the turn-on signal applied to U6E by either or both diodes CR16,CR18.

The heater and thermostat are used only in conjunction with a special low-temperature insulation system and are discussed later (sect. 6.1).

3. CONTROLLER LOGIC

Drive to the controller LED (CR3 of fig. 13) is supplied either by the LED enable flip flop U16B or by the RZ code generator. The sequence required at this LED to elicit proper function of the REMOTE UNIT logic is shown in figure 14. States of the ÷ 16 counter discussed below are shown as S0, S1,...S15. Assuming that the LED is initially enabled, i.e., remote power on, the preamble to the RZ code consists of a 5-ms low, 15-ms high, and 5-ms low. After this, at 6-ms intervals, the RZ code generator emits 8 pulses either 2 or 4 ms wide, depending on whether the bit in question is 0 or 1. After the RZ code ends the LED drive remains low for 15 ms, followed by a 10 ms high. The LED signal is then taken low and the local data receiver enabled to await readback of data from the remote unit. After the data have been received, the circuit will revert to its initial state. If data are not received, the circuit will revert to its initial state and indicate that a fault has occurred. This comprises the result of a SEND command when the remote unit is powered up. In all, four sequences are possible:

(1) SEND with REMOTE POWER ON
(2) SEND with REMOTE POWER OFF
(3) READ with REMOTE POWER ON
(4) READ with REMOTE POWER OFF

If sequence 2 is selected, the LED will be initially off, so a 5-ms high is inserted at the beginning of the SEND sequence. (Actually, this is part of sequence 1, but appears there merely as a delay in dropping the LED.) Sequences 3 and 4 are generated by skipping the first part of the SEND sequence as shown in figure 14.

The general arrangement of the controller logic is as follows: a 1-kHz two-phase clock is divided by 5 to establish a 5-ms clock. This increments a ÷ 16 counter, which acts as a control state counter, variously enabling the LED, the RZ code generator, and the data receiver. To avoid adding more counters and decoders to define the entire sequence, the counters are not incremented when either the RZ code generator or the receiver are enabled. When the ÷ 16 reaches its maximum count, both counters are again disabled. At this time, new data may be loaded into the RZ generator and remote power ON/OFF commands will be executed. Enabling the counters begins a new SEND sequence; READ is initiated by jamming the ÷ 16 to the appropriate state.

Normally, the circuit will be awaiting commands with U5, the ÷ 5 counter in state 1100 and U7 in state 1111. Note that the $\overline{\text{COUT}}$ of U7 is low, so on every ϕ_1 trailing edge the 0 will be clocked through U17B to one input of U15A, inhibiting the clock to the ÷ 5 so neither counter can advance. Note that the Q of U17B, now high, enables the parallel inputs to the RZ code generator shift registers U11 through U13. Furthermore, the decoder U8 is enabled, consequently enabling ϕ_2 clock to U16B. The D input to U16B is a debounced REMOTE POWER ON/OFF command, so that at this time the LED will be enabled for ON or disabled for OFF. The SEND sequence is initiated by an over-riding SET to U17B. (This, generated by U18B and U14C, must be made long enough to allow U5 to finish counting to 1111 and clock U7 to 0000, so that the output of the sequence enable FF U17B will stay true.) When U17B sets, the parallel data inputs are disabled and ϕ_1 clock to both counters resumes. Waveforms associated with the ÷ 5 counter and with the receiver enable sequence are shown in figure 17. This is a ÷ 15 up-counter with feedback to preset 1010 on the ϕ_2 pulse following a carryout. Race is avoided by sensing $\overline{\text{COUT}}$ = 0 on state 1111 at the trailing edge of ϕ_1. Gating this with ϕ_2 produces the preset enable (PE) pulse, which sets 1010, causing $\overline{\text{COUT}}$ to go high. The next ϕ_1 trailing edge causes U16 to change state,so that PE stays low until U5 once again reaches maximum count.

Note that the ÷ 16 counter U7 is incremented on the leading edge of the U5 $\overline{\text{COUT}}$, and its decoder, U8, enabled from the low state of the third LSB of the ÷ 5 counter. Decodes go true (high) on a ϕ_2 leading edge and go false 1.5 ms later on a ϕ_1 leading edge. We shall return to this point in the receiver description.

Decoded states S0, S2, and S9 are ORed together to set U16B while S1, S4, and S11 provide resets. Thus, when the counters are enabled, U16B is set by S0 (if it is not already set); 5 ms later, S1 goes true, resetting U16 and turning off the LED. After 5 more ms, S2 sets U16, which stays true until S5 resets it 15 ms later still, again turning off the LED.

After a wait of 5 ms, S6 goes true, clocking a 1 through U10A, the RZ enable FF. This disables both counters by setting the $\overline{\text{CIN}}$ of the ÷ 5 high, and at the same time enables U10B as a toggle flip-flop providing 500-Hz (2-ms) clocks to the RZ registers. This shift register was previously parallel-loaded with 16 fixed bits and 8 data bits B0-B7 in the following sequence starting from the output: 0, 1, B0,...0, 1, Bj,...0, 1, B7. Also, SER IN=0. Therefore, as the clock from U10B is applied to the shift register, 8 bits of pulse-width-coded data emerge from the register at the Q8 terminal of U13. This signal is inverted and (low-true) ORed (in NAND U2D) with the low-true output of the LED control FF U16B. When the last three stages of the shift register are empty, and ϕ_2 is true, the output of U15B goes true, resetting U10A. This disables the shift-out clock and enables both the ÷ 5 and ÷ 16 counters.

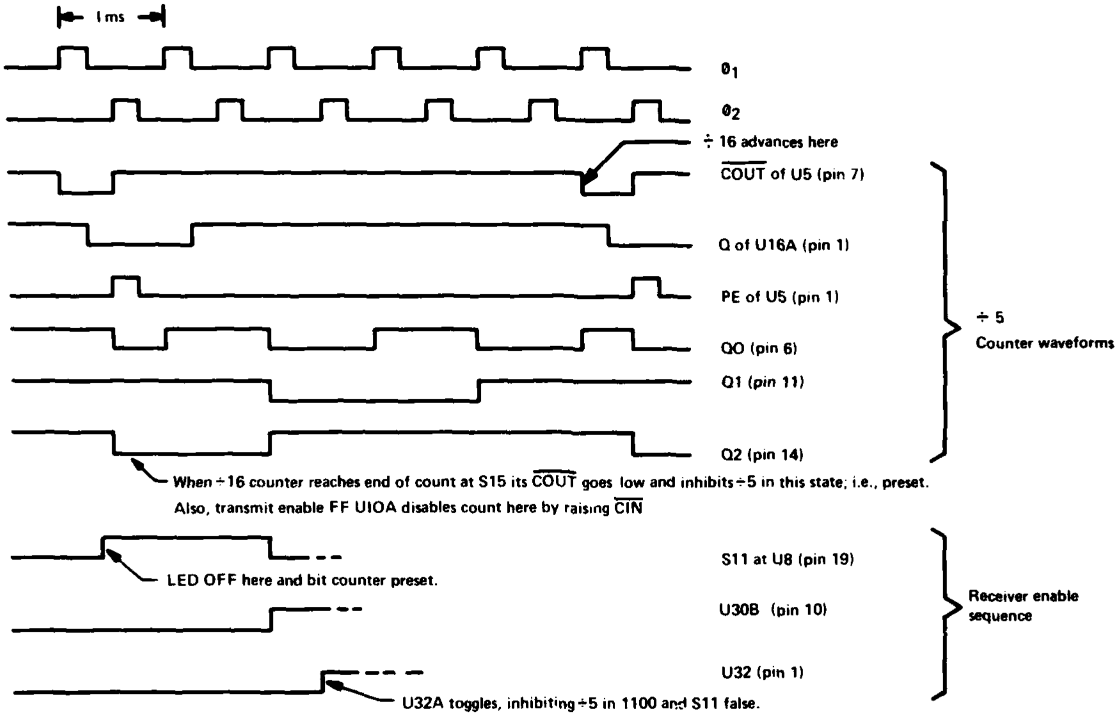


Figure 17. Detailed view of logic timing of controller during transmission/reception of commands and monitor data

About 15 ms later, S9 sets U16B high, lighting the LED for 10 ms until reset from S11. The leading edge of S11 drops the LED and also jams the received bit counter U31 to state 1000. The jam to U31 is released on the trailing edge of S11, which also triggers the one-shot U30B, the output of which is clocked through U32A to disable the state counters U5 and U7 and enable the receiver clock one-shot U30A. As pulse-width-modulated (PWM) data arrive from the comparator they are clocked into the receiver shift register U33A. The trailing edge of the 8th received bit causes the received bit counter to reach 0000, causing its $\overline{\text{COUT}}$ to fall. This inhibits further data pulses from either triggering U30A or clocking U31. If 8 pulses have not been received within the timeout of U30B, the cycle will complete in any case except that $\overline{\text{COUT}}$ will be high. The state of $\overline{\text{COUT}}$ is clocked into U32B when U30B times out, and buffered to the computer interface and to a front-panel LED to indicate a faulty read.

The above description of the remote control circuit has thus far ignored what actually is sent to the remote unit and what is received from it by way of status data. In the order that they emerge from the controller shift register, the eight transmit bits are assigned as follows:

TBO	3-dB attenuator
TB1	6-dB attenuator
TB2	12-dB attenuator
TB3	24-dB attenuator
TB4	Input select, LSB
TB5	Input select, MSB
TB6	Calibrator power
TB7	Spare

The logic convention is positive-true; i.e., TBO = 1 inserts the 3-dB attenuator.

The status word readback from the FO transmitter is similar but not identical:

RBO	3-dB attenuator status
RB1	6-dB attenuator status
RB2	12-dB attenuator status
RB3	24-dB attenuator status
RB4	Input selected, LSB
RB5	Input selected, MSB
RB6	Calibrator power
RB7	Low battery

As mentioned above, the readback circuitry in the transmitter inverts data, so that the word at the outputs of the receiver shift register U33 is negative true; the MOS/TTL buffers U37, U38, and U41 invert the signals once again so that the logic convention at J1 is again positive.

In addition to RBO through RB7, two other pieces of status information called RB8 and RB9 are generated in the controller. RB8 is high if the value of received photocurrent indicates that the laser is actually turned on and that it is being received by the optical analog receiver. This can be useful: for example, if REMOTE POWER has been commanded ON and READ invoked, a successful READ showing NO LASER on RB8 would suggest either a fault in the analog section, a broken optical fiber, or would verify a LOW BATTERY indication by making it clear that the automatic shutdown circuit had detected battery below tolerance and turned off power to the transmitter's analog circuits. This GO-NO GO indication is made available only to the computer interface; for manual operation, the actual photodiode current is indicated by a front-panel meter. RB9 indicates whether the expected 8 bits were received by the control unit receiver during the READ cycle. A failure to receive the entire 8 bits would mean that the data in the receiver shift register, U33, were not updated and that quite possibly all bits RBO through RB7 are incorrect. Such failure is indicated by lighting of the READ ERROR LED on the front panel and by appropriate data at the computer interface. The status of other functions is made available by U37, U38, and U41 as TTL signals to the computer interface by J1 and as front-panel LED indications by the associated drivers (U39, Q3 through Q9) and LED's (DS4 through DS14).

4. ANALOG OPTICAL RECEIVER

The analog receiver is pictured in figure 18 and its operational arrangement is summarized by the block diagram of figure 19. One may see from the diagram that the modulated laser beam emerges from the fiber and is incident upon the optical system which relays the light to a fast photodiode. The photocurrent is amplified by a two-stage wide-band amplifier and is brought out to the front-panel SMA output connector. An AGC scheme compensates for temperature effects on the detector and also for variations in the received optical signal resulting from fiber and fiber-connector losses.

4.1 *Optical System*

Although a readily recognizable fiber connector is seen on the front panel, no fiber-to-fiber connection is used at the receiver. The function of the front-panel connector is merely to hold the fiber termination rigidly in place at the focal point of the first lens, as can be seen in the sketch of the optical input system at the left side of figure 20. The first lens is one focal length from the fiber end; the second, one focal length from the detector. The distance between the lenses is not critical because the rays are practically parallel in this region. The fiber is imaged at unity magnification within the active area of the detector. The fiber core, 50 or 60 $\times$ 10^{-6} m in diameter is smaller than the diameter of the active area of the photodiode by a factor of more than 12, so that considerable tolerance to misalignment or defocus is inherent. A magnifying relay may be used if desired. It is, however, important for the control of modal noise that no rays emitted from the fiber end miss the detector area. Therefore, the numerical aperture (N.A.) of the system must be greater than the fiber N.A. of 0.2, so that each lens must have a larger relative aperture than roughly f2.4. At such a large relative aperture it is absolutely necessary to correct the spherical aberration of the lenses. This consideration makes necessary the use of achromatic lenses. Achromatism per se is not required in this monochromatic system; however, well-designed achromatic doublets are highly corrected for spherical aberration. The required neutral density and anti-Cerenkov bandpass filters are inserted between the lenses where the rays are nearly parallel.

Figure 18. High frequency optical receiver. Lens assembly at middle left, APD near center, bias control at right.

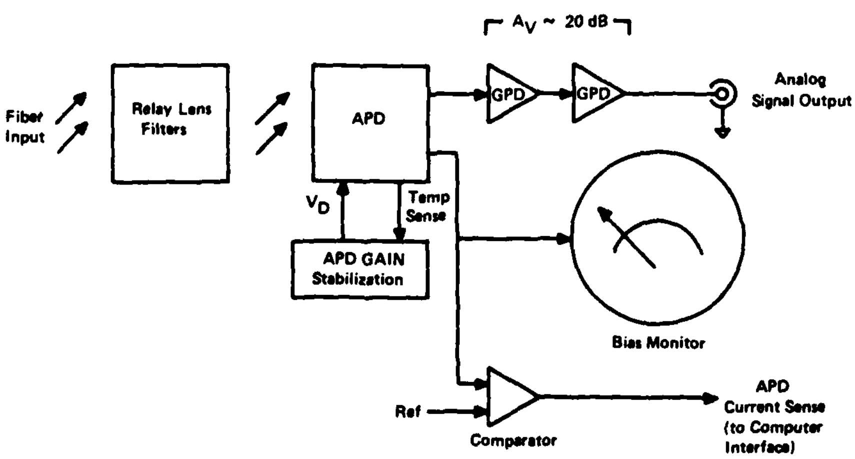


Figure 19. Block diagram of high frequency optical receiver.

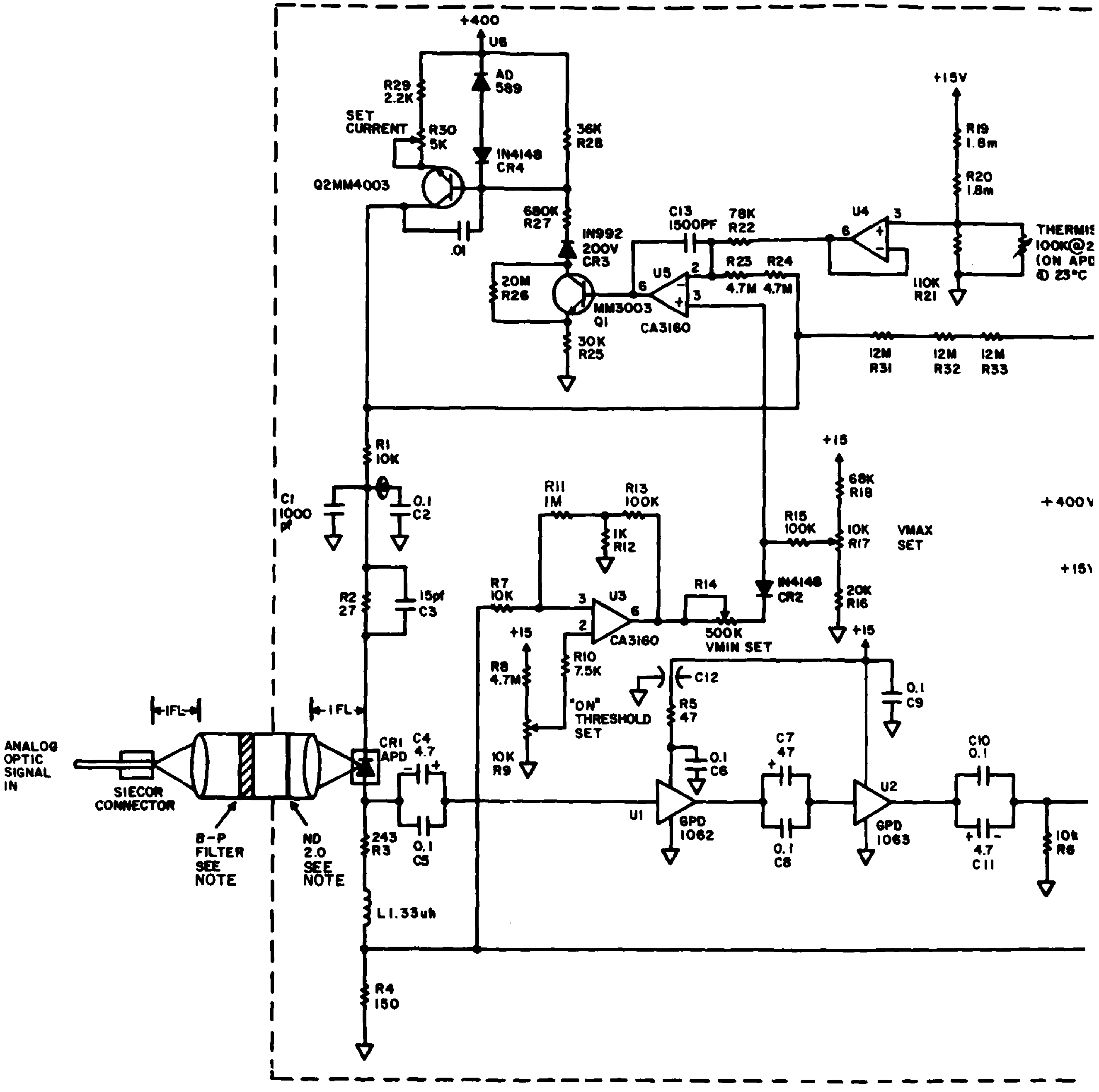
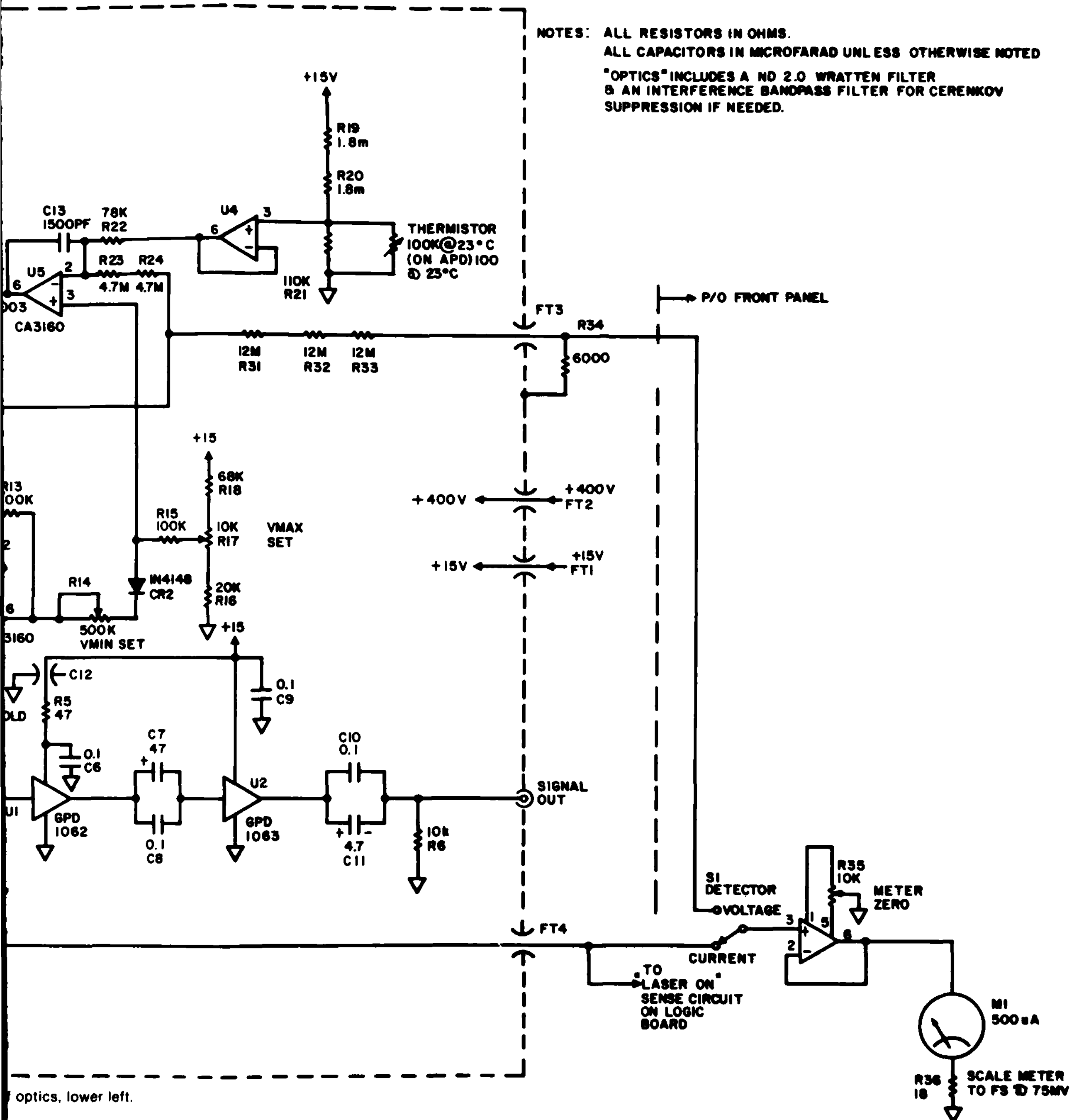


Figure 20. Schematic of high frequency optical receiver. Note arrangement of optics, lower left.

NOTES: ALL RESISTORS IN OHMS.
ALL CAPACITORS IN MICROFARAD UNLESS OTHERWISE NOTED
"OPTICS" INCLUDES A ND 2.0 WRATTEN FILTER & AN INTERFERENCE BANDPASS FILTER FOR CERENKOV SUPPRESSION IF NEEDED.



optics, lower left.

4.2 *Photodetector*

The photodiode selected for this application is a silicon avalanche photodiode (APD) made by RCA. The construction adopted by RCA results in a photodiode having equal rise and fall times. Most PIN detectors exhibit a two-component fall time (tailing) unsuitable for this application. The output current from the APD is amplified to the few hundred millivolts level by a two-stage amplifier constructed from standard Avantek parts. The APD is the bandwidth limiting element of the system, establishing the upper 3-dB point at 350 to 400 MHz. Using, for instance, a BPW-28 APD in the receiver the total system bandwidth was over 600 MHz, but the active area of this diode was so small as to create serious optical alignment problems.

4.3 *Automatic Gain Control*

Because the gain of the APD varies with applied voltage bias, it is possible to make a useful AGC. Q_2 and associated components provide a constant-average-current bias to the APD on the presumption that if the average signal level rises or falls on a long-term basis, so does the modulation in the same proportion. For ac coupled systems which transmit short, one-shot phenomena, this is a good assumption. Additional circuitry is included to deal with the current surges which would exist when turning the laser ON or OFF and to allow a higher maximum voltage at elevated temperatures. U4, U5, and Q_1 limit the maximum voltage applied to the detector. This limiting is essential because otherwise under dark conditions the current regulator would apply damaging voltage to the APD in its attempt to maintain the current. U5 compares the detector voltage at its (−) terminal to the reference applied to (+). If the detector voltage is excessive, Q_1 is turned off, and consequently Q_2. U4 and the thermistor correct the maximum voltage limit for temperature.

Under dark conditions the gain of the APD will rise to a maximum. To avoid a current surge when the laser illumination suddenly strikes it, the circuitry of U3 reduces the detector voltage under dark conditions. As soon as even a small current flows through the APD, CR2 unclamps and allows detector voltage and current to be controlled normally.

5. RS-232 INTERFACE

An RS-232 interface is provided so a computer can control link functions. Commands to the link include send, read status, transmitter power ON/OFF, calibrator enable, attenuator enable, and input select. The computer also monitors calibrator, input, attenuator, and battery status through the command link data register. Other status bits are allocated to command link read error and to analog detector current threshold.

The circuitry of the interface can be seen, mounted vertically, at the right-hand side of the controller cabinet, shown in figure 21. When the interface is in use the control inputs to the logic of the controller are connected to the command output latch rather than to the manual switches on the front panel. The LED indicators on the front panel remain operational at all times and the interface converts their indications to the correct sequence to be delivered to the computer.

The circuit diagram of the interface is shown in figure 22. Information is received from the computer through line receiver IC3, which shifts the RS-232 voltage levels to a standard TTL level. UART IC12 deserializes the data using 16X clock IC1. The parallel data come from the R0-R7 lines and are latched into IC6 or IC7 depending on which clock input is active on those units. The decision is made as to which latch gets the data mainly from UART bit R6. The data ready (DR) line from the UART's receiver is AND'ed with R6 by IC5A,B. The inverted signal from IC4A provides a one to ICA in the case that R6 is a zero so that the "first" byte is latched into IC6. IC5B latches the data in IC7 in the case that the "second" byte is selected. The information from IC4D (same as used to clock IC7) is fed into D flip-flop IC10. IC10 functions as an AND gate for the LINE signal and the "second" byte select line. The select information is clocked into IC10 by 16X clock IC1. This avoids a possible race conditon with the READ and SEND lines arriving the same time as the CAL POWER line. The READ and SEND will always arrive at the output one-half clock cycle after the data become ready at the UART (this is due to the way the UART functions). To avoid receive buffer overruns in the UART, it is advisable to reset the data ready signal after a byte has been received. This is done using IC11A.

When the command has been given to latch information into the buffers, either by IC5A or IC10B, a pulse from one-shot IC11A is applied to the DRR pin on the UART, resetting the DR line.

The three-state information from IC6, IC7, and the two-state information from IC5 is fed into a transistor stage for conversion from TTL levels to 12-V CMOS levels. When the information is three state, a 1-M resistor pulls the data up to the 5-V level, thus initiating a high level or an open-collector condition in the transistor. When a low level is input, the collector of the transistor is forced to a near-ground or zero condition. An exception for the POWER-ON and POWER-OFF signals had to be made since they cannot be used in an open-collector mode (the high signal on both outputs would cause an ambiguous condition in an RS flip-flop in the control logic). These two circuits were provided with a diode-resistor pullup pair for working in LINE mode; in local mode, the diode is reverse biased by the CMOS line/local signal from the front panel, thus disabling the pullup and allowing the pulldowns on the controller card to take effect.

Now to go in the reverse direction. When a SEND or a READ is initiated, the BUSY line becomes active. When it once again becomes inactive, the link has supposedly completed the designated operation and there is fresh information in the link in the controller's shift register. The BUSY line fires one-shot IC12A, which resets D flip-flop IC10A, which selects IC8, or the "first" byte of

Figure 21. Interior of controller/signal receiver. Controller is largest board, near center, RS-232 interface is vertical, on right.

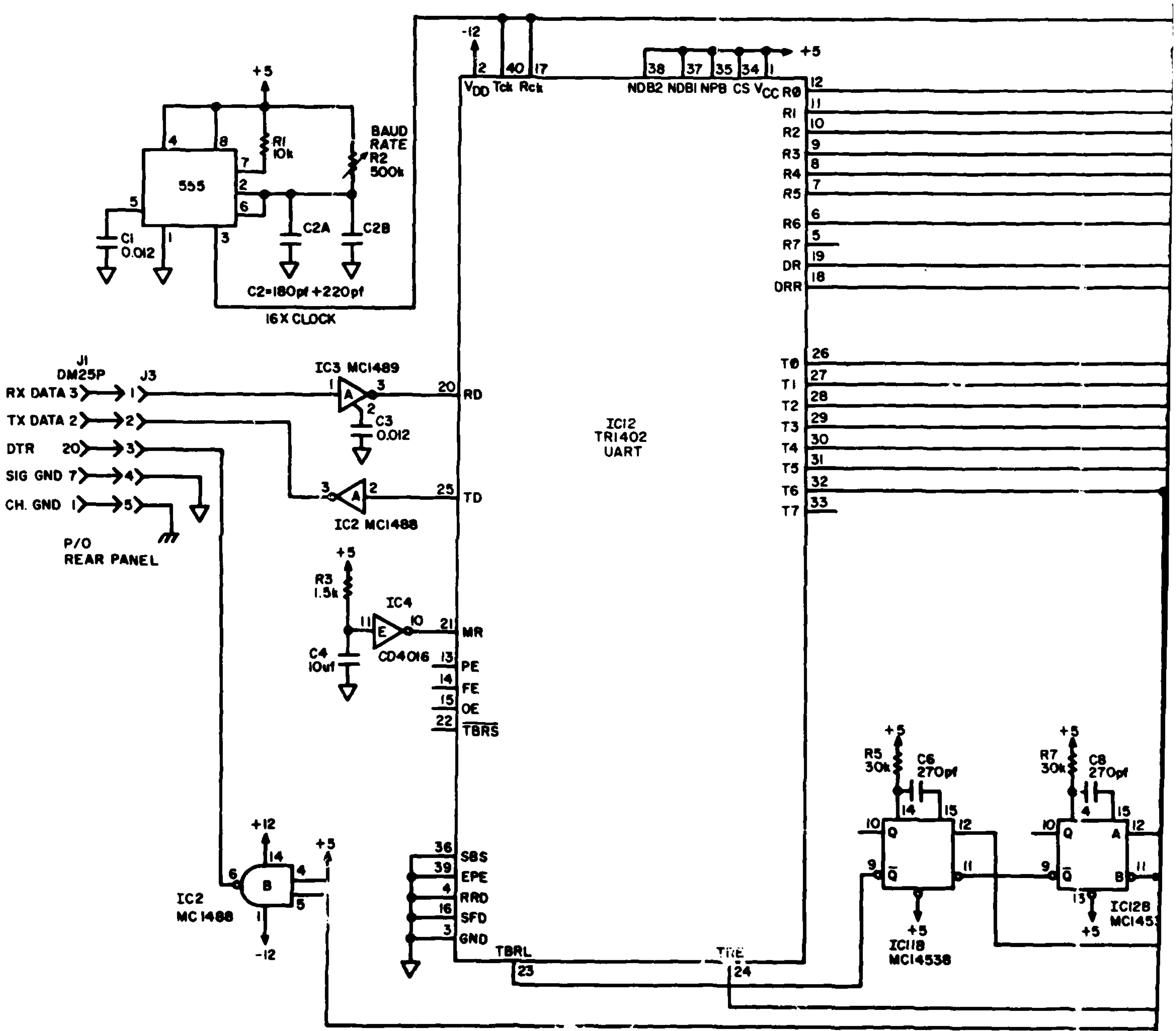
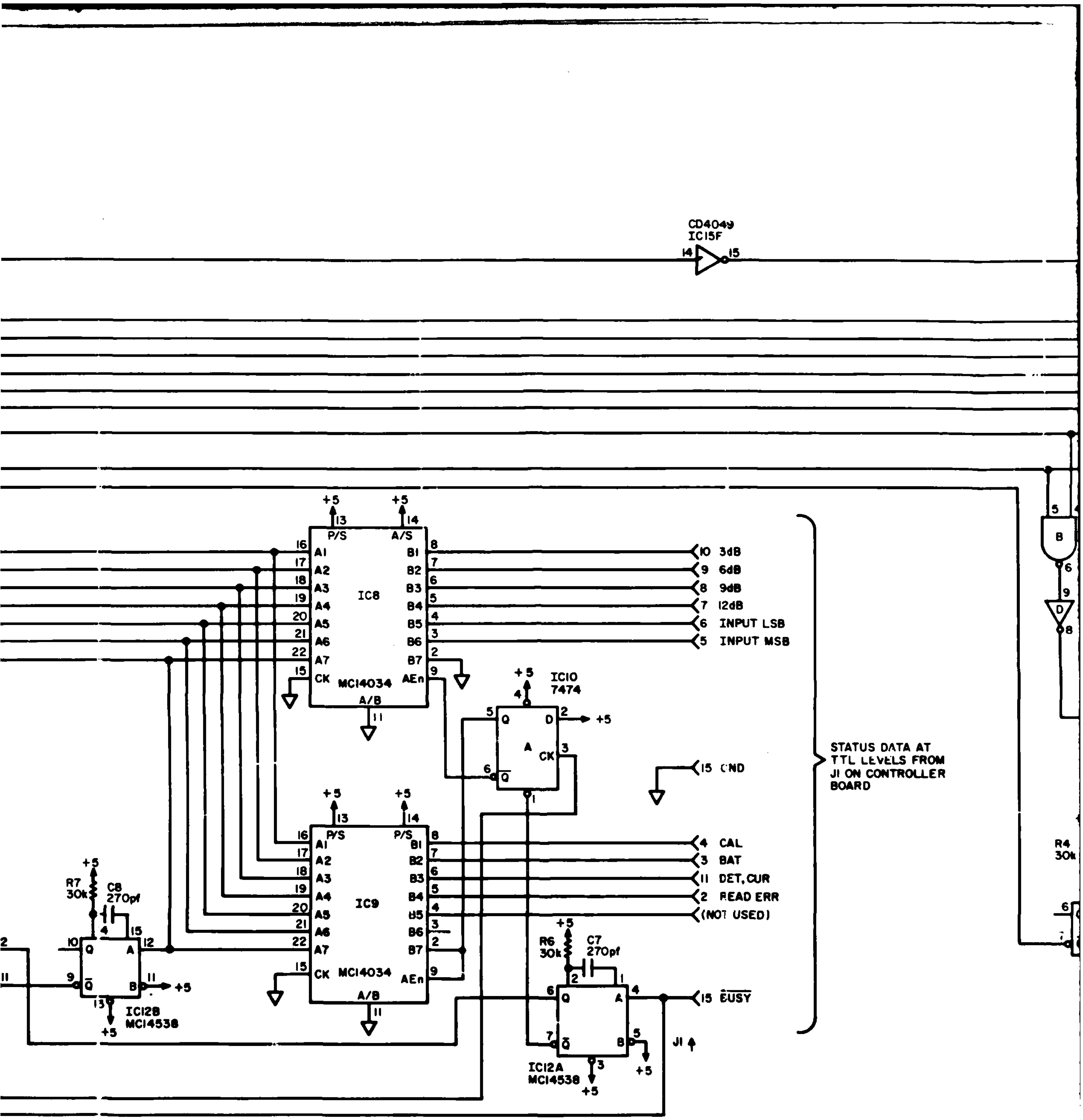
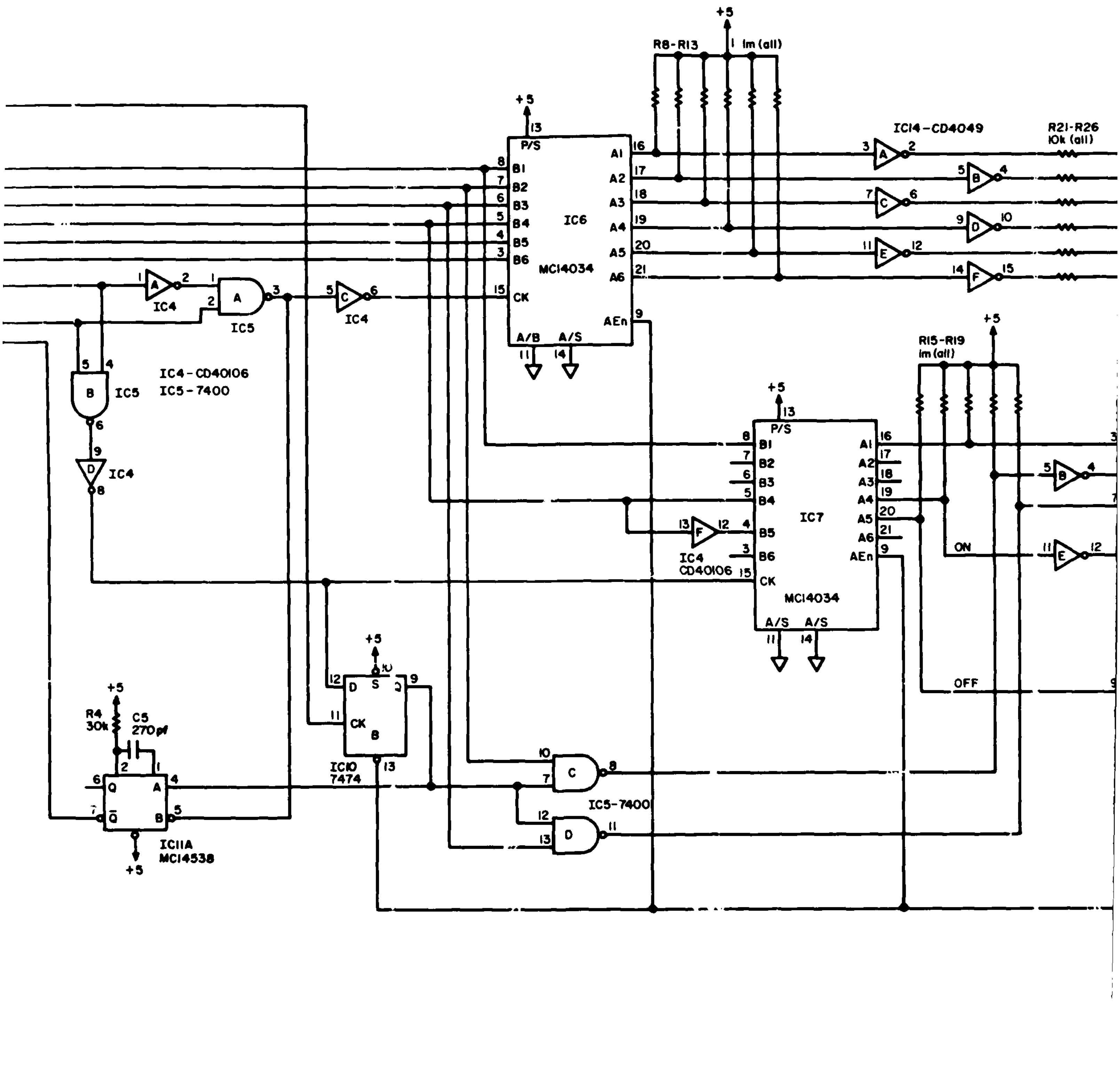


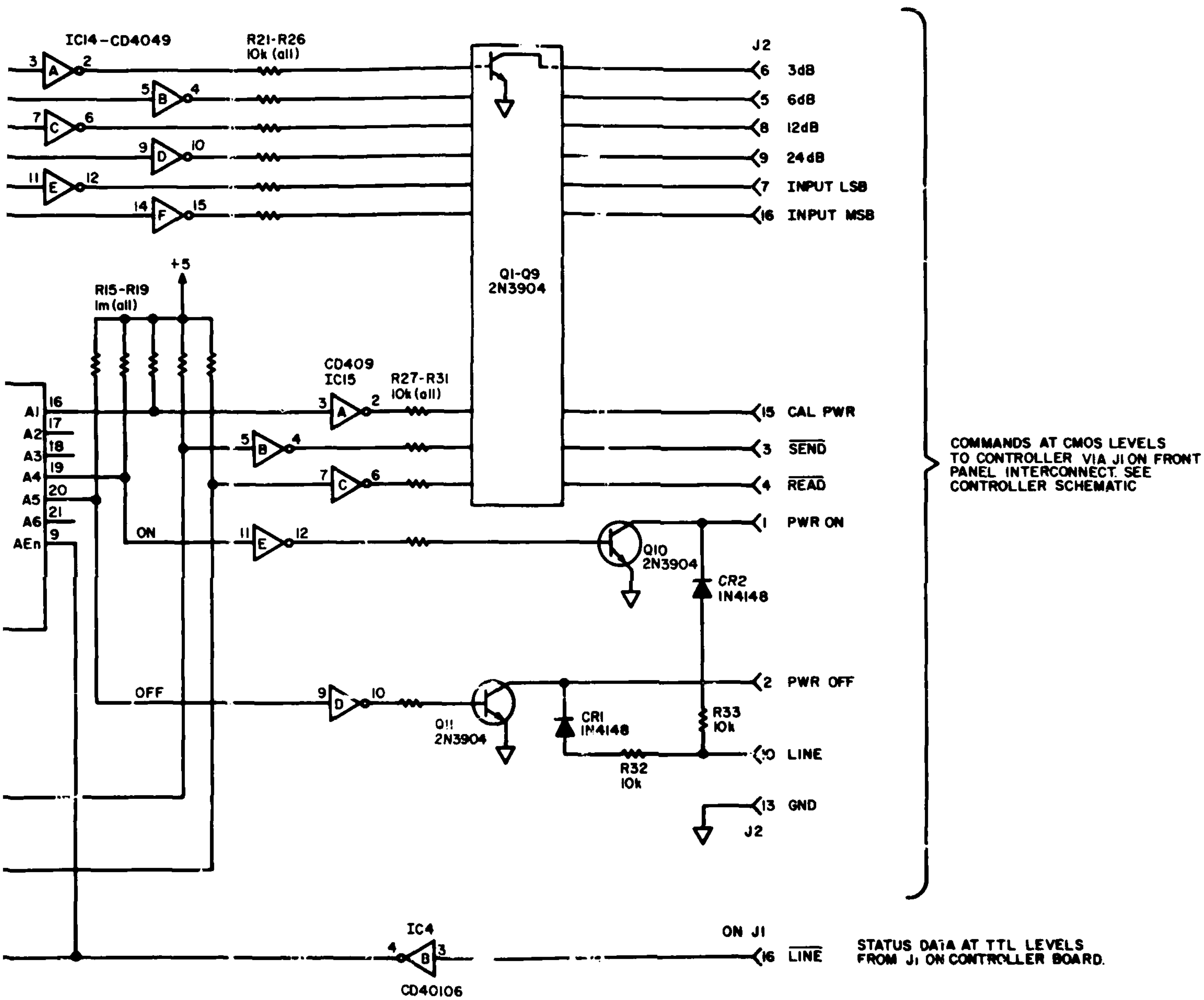
Figure 22. Schematic diagram of RS-232 interface.

1



CD4049
IC15F
IC8
MC14034
P/S
A/S
A/B
AEn
CK
10 3dB
9 6dB
8 9dB
7 12dB
6 INPUT LSB
5 INPUT MSB
IC10
7474
15 GND
STATUS DATA AT TTL LEVELS FROM J1 ON CONTROLLER BOARD
IC9
MC14034
4 CAL
3 BAT
11 DET, CUR
2 READ ERR
(NOT USED)
R7
30k
C8
270pf
IC12B
MC14538
R6
30k
C7
270pf
IC12A
MC14538
15 BUSY
J1
R4
30k


+5
R8-R13
1m (all)
IC14-CD4049
R21-R26
10k (all)
P/S
B1
B2
B3
B4
B5
B6
CK
A1
A2
A3
A4
A5
A6
AEn
A/B
A/S
IC6
MC14034
IC4
IC5
IC4-CD40106
IC5-7400
R15-R19
1m (all)
IC7
MC14034
IC4
CD40106
ON
OFF
IC10
7474
IC5-7400
R4
30k
C5
270pf
IC11A
MC14538



IC14-CD4049
R21-R26
10k (all)
J2
6 3dB
5 6dB
8 12dB
9 24dB
7 INPUT LSB
16 INPUT MSB
Q1-Q9
2N3904
+5
R15-R19
1m (all)
CD409
IC15
R27-R31
10k (all)
A1
A2
A3
A4
A5
A6
AEn
15 CAL PWR
3 SEND
4 READ
ON
1 PWR ON
Q10
2N3904
CR2
1N4148
OFF
2 PWR OFF
Q11
2N3904
CR1
1N4148
R33
10k
10 LINE
R32
10k
13 GND
J2
COMMANDS AT CMOS LEVELS TO CONTROLLER VIA J1 ON FRONT PANEL INTERCONNECT. SEE CONTROLLER SCHEMATIC
IC4
CD40106
ON J1
16 LINE
STATUS DATA AT TTL LEVELS FROM J1 ON CONTROLLER BOARD.

information to the UART's inputs. One-shot IC12A also fires, in turn, IC11B, which instructs the UART to load the input data by TBRL. After the serial data is sent from the UART, the TRE line goes high, clocking a one into IC10. This selects IC9, or the "second" byte of status information, and sets B6 on the UART to a one. This fires one-shot IC12B, which refires IC11B and instructs the UART to send a second byte of data. The BUSY line is also made available to the data-terminal-ready (DTR) line on the RS-232 connector to show that the link is, in fact, busy. This need not be used if no information is sent to the link before information is received from the link. R2, C4, and IC4E provide power-on reset to the UART. The RS-232 interface is hard-wired to operate with 8 data bits, no parity bit, and one stop bit. The 16X clock is set to produce a transmission and reception rate of 1200 baud.

6. TRANSMITTER TEMPERATURE CONTROL

The entire system (transmitter and receiver) will operate without special provision over the normal temperature range associated with laboratory equipment, 10 to 50 C or more. The only components having an uncommonly great temperature sensitivity are the APD and the laser and both are feedback stabilized.

For use in space simulators, where temperatures may approach those of the liquid-nitrogen cooled cryobaffles, special arrangements were necessary: a thermostat-controlled heater is placed in the transmitter housing and a separate highly insulated enclosure is slipped over the transmitter case.

6.1 *Heater*

The heater and its klixon-type thermostat can be seen in the Power System card in figure 9. The heater consists of two 50-ohm resistors, one of which can be seen underneath the balun in figure 7. The klixon-type thermostat operates the heater when the temperature falls below about 15 C.

Obviously, the batteries cannot operate the heater so it is isolated by CR1, CR2 and will operate only when the charging line is energized.

6.2 *Insulating Enclosure*

Figure 23 is an insulating enclosure into which the transmitter is placed for operation at extremely low temperatures. The enclosure is made like a thermos bottle. The outside of the inner box and the inner wall of the outer box are both buffed aluminum in order to minimize emission. These two boxes are mechanically attached to one another by small pads of foam insulation totaling only about 2 to 3 in.^{2}. This insulation is sufficient that only 2 to 3 W are required to keep the transmitter at 15 C even when the outer wall of the insulating enclosure is in contact with liquid-nitrogen coils.[6] The temperature of the transmitter fell only a few degrees an hour when the charging power was removed, and the heater thereby deenergized; this allowed plenty of time for data taking without significant temperature change.

If it is desired to operate the heater without battery charging it is necessary only to reduce the charging line voltage from the normal 28 to 32 to about 20 V; this closes K9, energizing the heater circuit, but is insufficient to cause current flow in the charging regulators.

7. OPTICAL FIBERS AND CONNECTORS

The great bandwidth of the analog link requires that a fiber having low modal dispersion be used. Good quality graded-index fiber such as Siecor 112 fulfills this requirement. The control link has no such constraint; however, it is likely more trouble than it is worth to specify a different fiber, particularly if both are cabled together within a common sheath. At the transmitter the fiber connection is made by means of a Deutsch immersion lens-type connector, as these incur far less modal noise than any butt connector. These connectors can

[6]*James C. Blackburn et al, Wideband Analog Fiber Optic Signal Link for the Space/Radiation Simulator Environment, Proceedings of SPIE,* **296**, *Fiber Optics in Adverse Environments (August 1981), 207-212.*

readily be made vacuum-tight,[7] and, in principle, be used to penetrate the tank wall. However, even less modal noise can be expected if penetration is achieved without using demountable connectors. At the receiver, a Siecor connector is preferred as it features precise, rigid, fiber location. The control link employs Siecor connectors chiefly because they were fitted to the fibers at the factory, but any connector of good quality will do as well. That portion of the fiber optic cable exposed to the x-rays and to the spacecraft charging electron spray will be protected by a lead-loaded plastic sheath.

[7]*James C Blackburn, High Vacuum Bulkhead Feed-Through for Optical Fibers, Applied Optics,* 19, *(September 15, 1980), 3035*

8. TESTING AND SPECIFICATION

The system was finished in late 1980 and has been used frequently since, much of the time in tests designed to check its performance, particularly in regard to radiation hardness. It has also been evaluated by the accidental hard knocks method, both in regard to physical and electrical stamina. No failures occurred, except in fiber optic cable connectors, nor have any readjustments been required except for some temporary fixes to compensate for defective optical connectors.

The results of the most extensive single performance test were published in 1981. The transmitter was simultaneously exposed to the temperature of

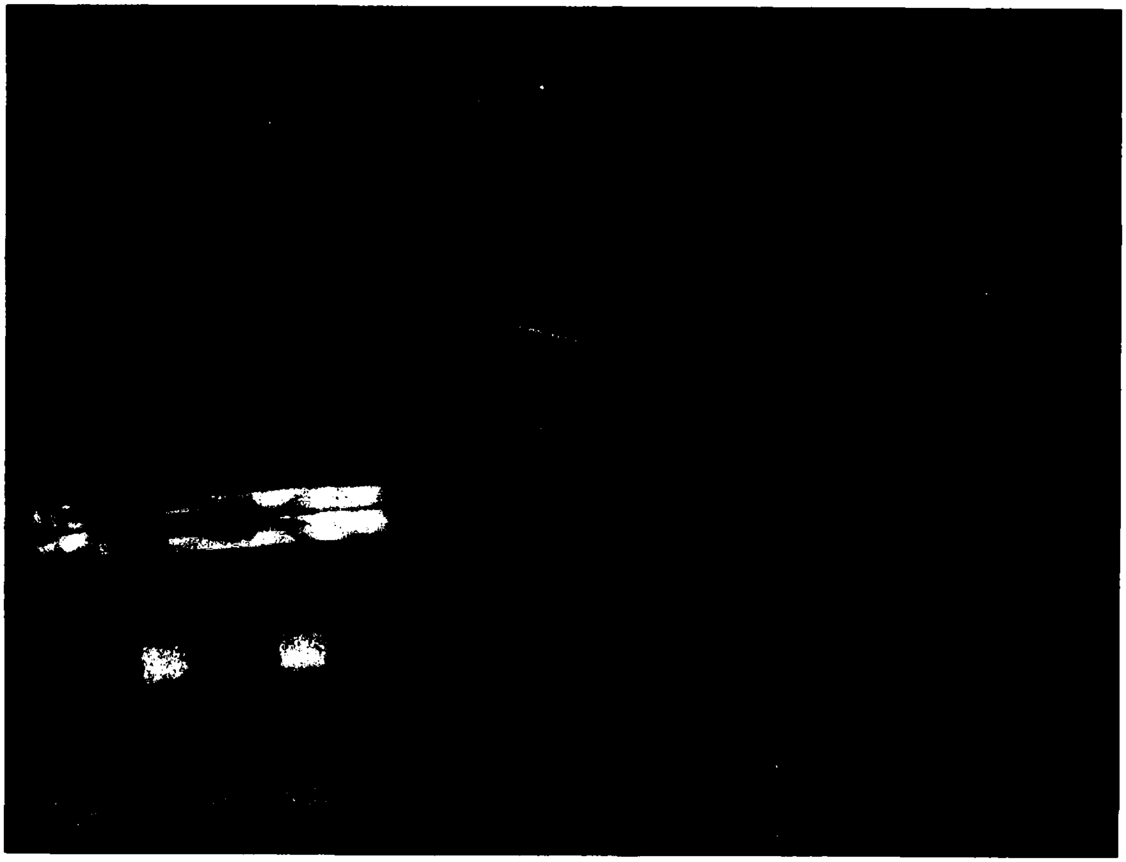


Figure 23. Thermal insulating enclosure for use with remote transmitter at cryogenic temperatures.

liquid nitrogen, vacuum, and a fluence of 10^{12} elec/cm^2 of 1000-keV electrons. No effect was visible under this onslaught.

Data obtained with the HIFX flash x-ray determined that radiation-induced noise equal to normal system noise was produced when the transmitter was exposed to $\sim 10^8$ rad/s of ~ 1 MeV gamma radiation.

Optical fibers are affected by radiation and thus must be chosen carefully if they are to be exposed to ionizing radiation. The general subject of fiber performance is too extensive to be covered here, and also changes rapidly with new developments. Oldham et al[8] report some work done specifically in support of this system.

Since impedance matching and common-mode rejection were felt to be critical the baluns were extensively tested to assure adequate performance. The test methods and results are given by Vanderwall.[1] Input reflections were smaller than 5 percent in a 4-GHz TDR. Common-mode rejection was greater than 50 dB up to 50 to 100 MHz and decreased to somewhat more than 30 dB at 500 MHz.

Other pertinent electrical specifications not already mentioned include:

Rise and fall time: $\leqslant 1$ ns with < 5-percent preshoot or overshoot.

Receiver output: ~ 200 mV into 50 ohms (for full signal input)

Calibrator: adjustable, normally set to produce output equivalent to ± 25 mV at input (with zero attenuation). May be reduced in calibrated 3-dB steps via remote control.

[1]*Jonathan Vanderwall, An Improved Balun for the SXTF Fiber Optics Link, Proceedings of the Fiber Optics in the Nuclear Environment Symposium, Harry Diamond Laboratories, March 1980, Vol II, Radiation Physics (DNA 5308P-2).*

[8]*Timothy R. Oldham, et al, Selection of an Optical Fiber for the Radiation Environment of the Satellite X-Ray Facility, Harry Diamond Laboratories, HDL-TM-80-22 (July 1980).*

Dynamic range: <35 dB; lower end of dynamic range is noise level, as measured by tangential method with 500-MHz bandwidth. Upper end of dynamic range is the maximum signal input for which all harmonics are below fundamental by as much as fundamental is above noise level.

Bandwidth: <20 kHz (limited by balun) to >350 MHz (−3 dB) (limited by APD).

Physical specifications of transmitter:

Weight: 2-1/6 lb with batteries

Dimensions: 6-1/8 × 3-1/2 × 3-3/8 inches without insulating enclosure; with insulation, 6-5/8 × 4-1/2 × 4-3/8 inches.

Temperature range: 10 C to 45 C, with insulation to below −200 C.

9. DISCUSSION

The chief limitation on system performance is that set by noise, which establishes the floor of the dynamic range. The principal source is modal noise, engendered by the highly monochromatic laser used in the link. The advantages of this laser are its exceptional linearity and low drive power requirements. Even at this writing (mid-1982) multimode lasers, though effective at reducing modal noise, do not approach the low threshold current of these single-mode lasers. Nor is great linearity inherent in multimode lasers; selection is necessary. Despite the increased cost of such selection, their adoption might prove worthwhile in reducing modal noise, particularly if multiple fiber-to-fiber connections are needed, as for tank penetrations. Arnold and Petermann[9] show that lasers oscillating in several longitudinal modes, such as the V-groove structure, also have the potential for a lower intrinsic noise than that of the single-mode laser. This advantage is realizable only if the multiple modes are uniformly detected; it may be nullified if material dispersion in log fiber lengths produces phase differences, at the receiver, between the various laser modes. We are currently in-

[9]*G. Arnold and K. Petermann, Intrinsic Noise of Semiconductor Laser in Optical Communication Systems, Optical and Quantum Electronics,* **12** (1980), 207-219.

vestigating the intrinsic noise performance of a V-groove laser in a system optically similar to the one described here.

Using such a reduced-coherence laser might also permit an increase in system bandwidth, by reason that the dither modulation could be deleted so that the full modulation bandwidth of the laser would become available. This would entail a change to a faster APD in the receiver, which in turn forces far smaller tolerances on the optical design than were necessary before. Thus, no direct subsititution of a faster detector is possible; mechanical and optical redesign is required.

We have been successful in much simplifying the AGC circuit for the APD,[10] eliminating many of the components associated with U4 and U5 of figure 20. Furthermore, the no-signal bias reduction afforded by U3 appears to be unnecessary. Personal communication from RCA suggests that the current surge at laser turn-on would be too small to damage the detector diode.

In view of experience gained after construction of this transmitter, it appears that the laser case could be floated, and connected to a positive supply, rather than being grounded. This would allow elimination of the negative battery supply. Laser case-to-ground bypassing adequate to eliminate parasitics is difficult but appears realizable.

[10]James C. Blackburn, A Fiber Optic Signal Link for use with Microwave Field Sensors, presented at the National Conference on High Power Microwave Technology, Harry Diamond Laboratories (March 1983).

It should be mentioned that an IEEE-488 interface has also been built for this unit. This is a more modern design than the RS-232, using an 8085 micro and a TMS 9914 bus chip A meaningful description would require a lengthy PROM listing, etc., and is outside the scope of this report.

10. CONCLUDING REMARKS

The system has been in use for more than a year and a half with no electronic problems, not even a need for adjustments. In this time, no laser aging effects are evident. The only less-than-satisfactory performance has been that of the optical fiber connectors which, from time to time, have had to be fiddled with, cleaned, and even replaced. Fortunately, the state of connectors is still improving.

It should be noted that the compact, tested, and low-cost designs of the attenuators, amplifiers, and control circuits make good basic building blocks for incorporation into other systems using LED's or alternate lasers. These circuits are relatively easy to build in that the component count is suprisingly low and because these components attach directly to printed circuit boards.

We are continuing to evalute other lasers to determine the most favorable trade-offs between modal and competition noise, speed, linearity, and availability. Almost any type of optical source could be substituted for the specified laser with only modest changes in the present circuitry. Quite possibly, the V-groove structure will become the laser of choice for this system.

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(9) G. Arnold and K. Petermann, *Intrinsic Noise of Semiconductor Laser in Optical Communication Systems*, Optical and Quantum Electronics, **12** (1980) 207-219.

(10) James C. Blackburn, *A Fiber Optic Signal Link for use with Microwave Field Sensors*, presented at the National Conference on High Power Microwave Technology, Harry Diamond Laboratories (March 1983).

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